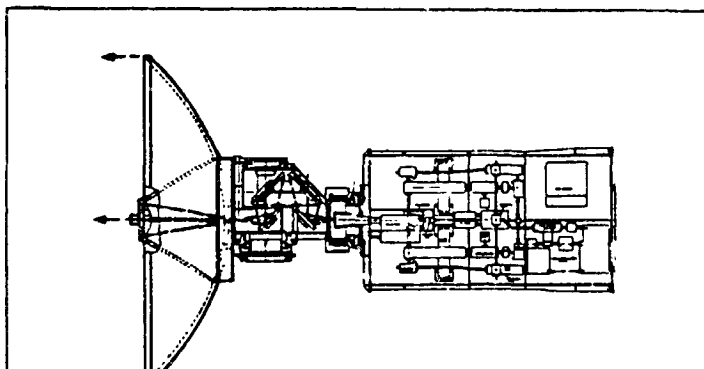


NASA CR- 175285

**60 GHz ANTENNA SYSTEM ANALYSES
FOR
INTERSATELLITE LINKS
PHASE A - FINAL REPORT**



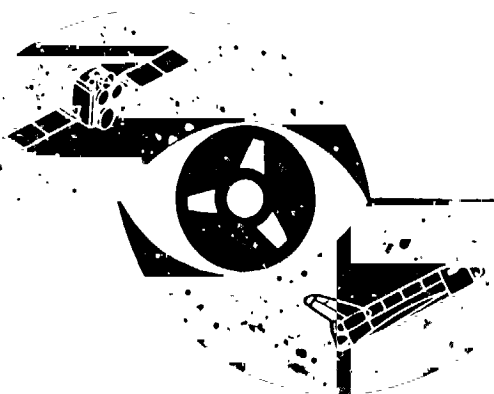
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June 1984

60 GHz ANTENNA SYSTEM ANALYSES
FOR
INTERSATELLITE LINKS
PHASE A - FINAL REPORT

Prepared For
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
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Contract NAS-5-27791
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1. INTRODUCTION AND SUMMARY

This report covers Phase A of a 2-phase study conducted by General Electric for NASA-Goddard Space Flight Center, under Contract No. NAS-5-27791. Phase A is a tradeoff study for 60 GHz antenna systems applicable to an advanced Tracking and Data Acquisition System (TDAS). Phase B will provide a conceptual design of a preferred antenna system to be selected by NASA-GSFC. In this Phase A report the tradeoff results for four types of antenna systems are presented:

Type B: Reflector/fixed feed (4 candidates)

Type M: Mechanical scan (4 candidates)

Type E: Electronic scan (3 candidates) and

Type H: Hybrid mechanical/electronic scan (1 candidate).

The 12 candidate antennas were assessed on the basis of a preliminary design and a performance analysis and then were scored against 15 weighted parameters. This process resulted in the ranking of the 12 candidates for the two applications, namely, for the geostationary TDAS only with a narrow field of view and for low orbit user satellites with a wide field of view.

For both applications the beam waveguide gimbal/Cassegrain reflector system (B1) is a clear winner scoring high in several important parameters such as volume, spacecraft impact, weight, insertion loss and power. There are only two other candidates with the capability of a wide field of view, namely, a system where the RF electronics is mounted on the back of the reflector (B2), thereby avoiding lossy RF rotary joints and a conventional gimbal system employing multiple (for auto-track error signals) RF rotary joints (B4) where the RF loss must be compensated by a larger antenna aperture.

All the other candidates have only a narrow field of view capability. The mechanical scan system (M4) using a fixed feed and fixed paraboloid reflector and a flat plate reflector movable by a 2-axis gimbal scores almost as high as the beam waveguide system (B1). In addition to high scores for insertion loss and power the flat plate reflector system wins out in high reliability and low development risk--it has successfully flown on the MIT Lincoln Lab LES 8/9 synchronous satellite.

Electronic scan systems pay an exorbitant price in complexity, development risk and cost for the feature of beam agility which is not important for the modest dynamics of the TDAS orbital scenario. The other beneficial feature, namely, inertia free beam scanning cannot outweigh the disadvantages.

During Phase B a more detailed conceptual design will be performed for the system to be selected by NASA-GSFC. This design activity will cover the electrical and mechanical antenna system configuration including antenna pointing and autotrack, control electronics and the impact on the host spacecraft. An overall performance summary will be compiled. The technology development status will be assessed for three identified topics:

Monopulse Front End

Flexible Waveguide

Rotary Joints.

A final report will be issued covering Phase A and B results.

NOTE: This Phase A Report also contains General Electric's response to the comments and questions submitted by NASA-GSFC resulting from their review of the Phase A Draft Report. General Electric's response is covered in Appendix F, found in the main part of this report, as applicable, and as noted.

2. SCHEDULE AND OVERVIEW

SCHEDULE

It is planned to adhere to the schedule established in December 1983 - with completion of the study by May 1984. Phase A is now completed and this report is the Phase A Final Report. Phase B will start immediately after selection of the preferred antenna system(s) by NASA-GSFC. Technology surveys into the topics of monopulse front ends, flexible waveguides and low loss rotary joints are identified as Phase B activities and are underway.

General Electric would like to express its readiness to consider additional and/or modified requirements for this ongoing study resulting from the continuing evolution of the IDAS system requirements.



TASK NO.		SUB-TASK NO.		OPER. NAME	PREPARED BY	DATE	APPROVED BY	DATE	ISSUE NO.
				Comm. Engineering	R. Heller	12-9-81			
				C-APPROVED TIME SCHEDULE					
				<div style="display: flex; justify-content: space-between;"> <div> (INDICATE YEARS) 1983 Sep Oct Nov Dec Jan Feb Mar Apr May </div> <div> 1984 Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May </div> </div>					
				<div style="display: flex; justify-content: space-between;"> <div> Award of Contract Modified SON Negotiated Phase A - T/O Analyses - Presentation - Draft Report - Final Report </div> <div> Phase B - Conceptual Design - Draft Report - Final & Summary Report </div> </div>					
				<div style="display: flex; justify-content: space-between;"> <div> START COMPLETE </div> <div> TIME PERIOD OF WORK </div> </div>					

Design Goal Specifications

Here the major antenna system parameters are listed as defined in the original SOW for TDAS only and as modified - at the suggestion of General Electric - to include both TDAS and the low orbit user requirements. The major difference between the two SOW's is the field of view (FOV) which widens from a cone of $\pm 13^\circ$ for TDAS to $\pm 126^\circ$ for a user at the specified maximum user orbit altitude of 1500 km (see Appendix C).

The modified SOW forms the basis of the subject study.

The following comments are made with respect to some of the antenna systems parameters:

- o Frequency - The choice of 60 GHz will give considerable relief on antenna sidelobe requirements since atmospheric attenuation at 60 GHz will nearly eliminate terrestrial interference and horizon multipath effects.
Related to frequency is the question of RF bandwidth. The specified five 50 megabit channels require a bandwidth in the order of $5 \times 0.05 = 0.25$ GHz representing only 0.4% relative bandwidth at 60 GHz. Thus, none of the antenna candidates should be bandwidth-limited. Selection of a frequency plan to enhance resistance to RFI caused by self and/or outside interference will not be considered in this study.
- o Antenna Gain - 54 dB of antenna gain requiring 4' antennas, 1 watt of RF power and a mixer noise figure of 5 dB at 60 GHz providing a 50 megabit link represents a balanced system for today's state-of-the-art (see Appendix D for link budget).
- o Data Rate Capability - With Landsat D at 85 megabits and the planned UARS at 0.5 megabits - as typical examples - a wide range of data rates is encountered which will need to be accommodated at Ku and 60 GHz.
- o Linked Spacecraft - It should be noted that for the TDAS forward link, i.e. TDAS to user, the TDAS EIRP requirements for command and tracking may be quite modest - as low as 1 kbit data rate which is 47 dB below the specified 50 megabits.
Alternately the G/T requirement for a user satellite may be reduced accordingly.
A further observation could be made: Since it is not realistic to assume that one single antenna system will accommodate TDAS and all possible future users, it is important that the selected design concept exhibit a maximum of design modularity and flexibility, e.g. a gimbal system that can handle various antenna sizes.
- o Field of View - A user FOV of $\pm 126^\circ$, while theoretically possible, is not practical due to structural self interference. A detailed configuration study for a beam waveguide system on a related program indicates a FOV of about $\pm 90^\circ$.



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60 GHz ANTENNA SYSTEM DESIGN GOAL SPECIFICATIONS



	<u>ORIGINAL 50W - TDAS ONLY</u>	<u>MODIFIED 50W - TDAS AND USERS</u>
Frequency:	60 GHz	Same
Antenna Gain:	54 dB including losses (referenced to right hand circular polarized isotropic antenna)	Same
Polarization:	Right hand circular	Same
Link Accommodations:	5 individual pairs of forward and return links under simultaneous operation	Up to 5 individual - -
Data Rate Capability:	Up to 50 x 10 ⁶ bits/sec per link	Same
Host Spacecraft:	Tracking and Data Acquisition System (TDAS) Satellite	--- And TDAS User Spacecraft
Field of View:	26° cone from geosynchronous orbit centered about the earth	26° cone or wider
Pointing Accuracy:	±.05 degree	Same
Linked Spacecraft:	5 earth orbiting satellites with altitudes ranging from 200 to 1500 Km, any inclination - it is assumed that each has a reciprocal antenna system with similar gain and link accommodations	TDAS (Geosynchronous) and 5 earth ---
Special Required Features:	Antenna pointing and control system (APCS) - use of dedicated on-board microprocessor; to maintain pointing accuracy. Autotrack Subsystem - required feature built into the APCS. Receiver/Transmitter Mounting - allowance for local mounting of receiver front end and transmitter final output stage directly at antenna sum channel port.	Same

Study Flow Plan

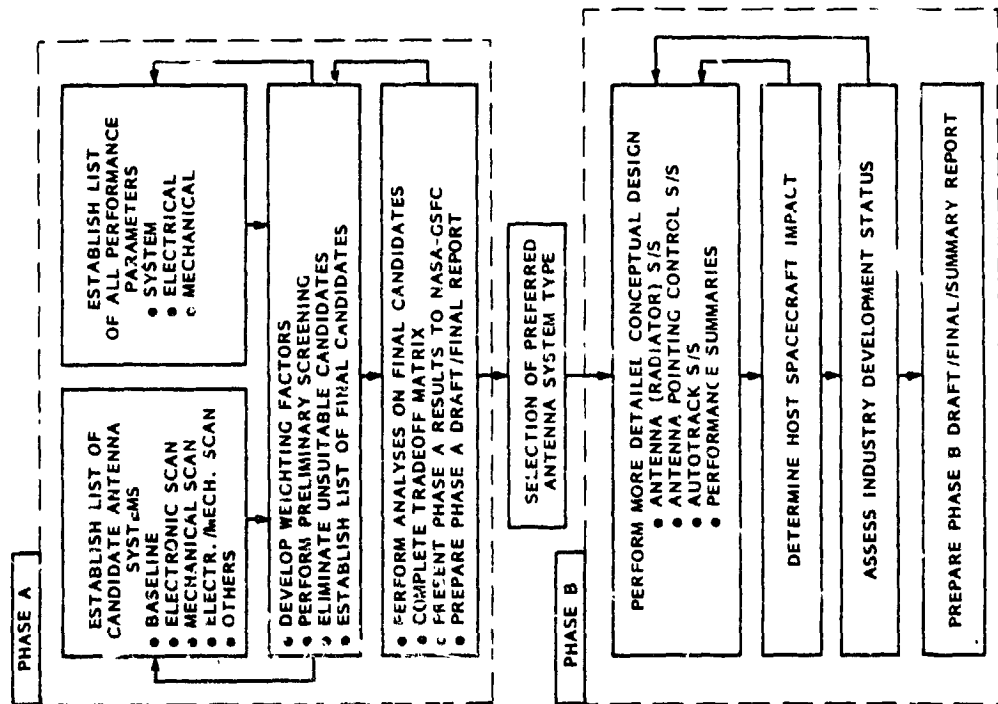
The study flow plan presented in the proposal is being followed. During the Phase A tradeoff studies a list of candidate antenna systems was established for the four specified antenna categories. The list of specified performance parameters used for scoring was reviewed and modified and will be discussed below. The weighting factors selected will be discussed below. All candidates were then systematically evaluated and after several iterations the tradeoff scoring matrix was completed. Several detailed analyses were performed and will be referenced in the discussion of the individual candidates.



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STUDY FLOW PLAN



Modified Phase A Tradeoff Matrix

This chart presents the modified matrix of performance parameters and lists all antenna system candidates under evaluation. The purpose of the chart is to review the original list of performance parameters as contained in the proposal and present the justification for the changes made during the tradeoff process.

- o Description - Not a parameter.
- o Complexity Electrical - Too general. Complexity is reflected in the individual electrical performance parameters and also in reliability, development risk and cost.
- o Complexity Mechanical - Too general. Complexity is reflected in the individual mechanical performance parameters and also in reliability, development risk and cost.
- o Commonality With Other Spacecraft - Not applicable. The antenna types clearly divide into two groups; one group with limited FOV which by definition does not have commonality and the other group with a large FOV which inherently has commonality.
- o Communication System Interface - Readily satisfied in all cases.
- o System Integration and Test Impact - This is a new parameter at the system level which was identified during tradeoff discussion and as a result of past experience with similar payloads.
- o Gain - Not applicable. Gain is a specified parameter. It must be achieved, Ease or difficulty to achieve it will be reflected in other parameters such as weight, power, cost, etc.
- o Beam Crossover - Covered by gain specification.
- o Field of View Coverage - Not applicable. It is a firm requirement.
- o Pointing Accuracy - Same.
- o Loss Budget - Changed to "Loss" which is the actual performance parameter. While covered by "Gain" it is included separately because it is a measure of overall system efficiency.
- o Autotrack Capability - Not applicable. It is a firm requirement.
- o Feed Network Requirements - Not important.
- o New Developments - Covered by "Development Risk" above.
- o Gimbal Requirements - Too general.
- o Fabrication Complexity - Covered by "Cost" and "Development Risk".
- o New Developments - Covered by "Development Risk" above.
- o Tolerances - Covered by "Cost". Reflector tolerances at 60GHz are 1 sigma ≤ 0.003 " for a gain loss not exceeding 0.2 db. This is within the present state-of-the-art.
- o Quality Assurance/Test Requirements - Covered by "System Int./Test Impact" above.



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60 GHz ANTENNA SYSTEMS ANALYSES
FOR INTER-SATELLITE LINKS



PHASE A TRADEOFF MATRIX

PERFORMANCE PARAMETER	WEIGHTING FACTOR	BASELINE TYPE REFL. FIXED FEED					MECHANICAL SCANNING					ELECTRONIC SCANNING					HYBRID ELEC/ MECH SCANNING				
CONFIGURATION NO.		B1	B2	B3	B4	B5	M1	M2	M3	M4	M5	M6	E1	E2	E3	E4	E5	H1	H2	H3	H4
SYSTEM																					
DESCRIPTION																					
COMPLEXITY - ELECTRICAL																					
COMPLEXITY - MECHANICAL																					
RELIABILITY																					
DEVELOPMENT RISK																					
CGST																					
HOT SPACECRAFT IMPACT																					
COMMONCRAFT WITH OTHER SPACECRAFT																					
COMMON SYSTEM INTERFACE																					
SYSTEM INT/TEST IMPACT																					
ELECTRICAL																					
CAMB																					
BEAMWIDTH																					
BEAM CROSSOVER																					
FIELD-OF-VIEW COVERAGE																					
SIDELobe LEVEL																					
POLARIZATION PURITY																					
POINTING ACCURACY																					
LOS SENSITIVITY																					
AUTOTRACK CAPABILITY																					
MICROPROCESSOR REQUIREMENTS																					
FEED NETWORK REQUIREMENTS																					
NEW DEVELOPMENTS																					
MECHANICAL																					
SIZE/TOWAGE																					
WEIGHT																					
POWER																					
EMERAL REQUIREMENTS																					
TORQUE NOISE																					
FABRICATION COMPLEXITY																					
NEW DEVELOPMENTS																					
TOLERANCES																					
ENVIRONMENTAL PROTECTION																					
QUALITY ASSURANCE/FEST-REGR																					
PROPOSAL																					
FIG																					
ANTENNA SYSTEM TYPE																					
2.2.1-1a/2a BEAM WAVEGUIDE FEED, CASSEGRAIN REFLECTOR																					
2.2.1-1a/2b FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET																					
2.2.1-1a/2c FIXED FEED, CASSEGRAIN, FLEXIBLE WAVEGUIDE																					
-																					
FIXED FEED, CASSEGRAIN, ROTARY JOINTS																					
MOVABLE FEED, DUAL FIXED REFLECTORS																					
MOVABLE FEED, SINGLE FIXED LENS																					
FIXED FEED, DUAL REFLECTORS, MOVABLE PARABOLOID																					
FIXED FEED, DUAL REFLECTORS, MOVABLE FLAT PLATE																					
PHASED ARRAY																					
PHASED ARRAY FEED, DUAL FIXED REFLECTORS																					
MBA FEED, DUAL FIXED REFLECTORS																					
PHASED ARRAY FEED, DUAL REFLECTORS																					
MOVABLE PARABOLOID																					

NOTE: The next four charts present the antenna configurations in the four specified generic categories with a brief introductory description. Each configuration is later presented and discussed in more detail.

Baseline Type - Reflector/Fixed Feed

This category is characterized by a fixed feed, i.e., a feed fixed with respect to a Cassegrain reflector system. In the case of B1 (beam waveguide) the feed is physically fixed to the spacecraft but a virtual feed moves with the reflector. B3 and B4 represent more conventional approaches using rotary joints or flexible waveguides to provide antenna articulation. In B2 all or part of the R.F. equipment is installed in a pallet on the reflector. Note that this is the only category with the potential for wide FOV (Configurations B1, B2 and B4). Since this category is inherently single-beam, 5 separate antenna systems are required to provide the 5 simultaneous links for TDAS.

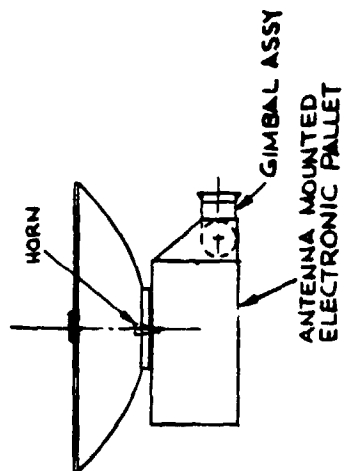
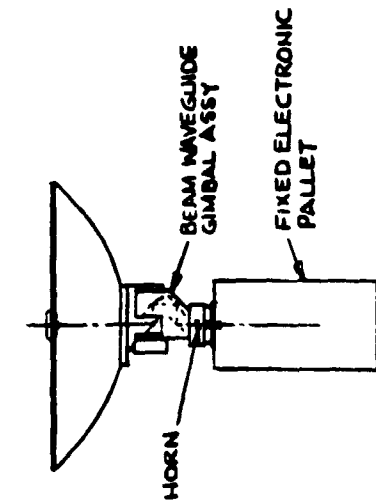
An additional concept where the reflector/pallet arrangement of configuration B2 is replaced by a distributed array of low power, fixed phase elements is described in Appendix E.



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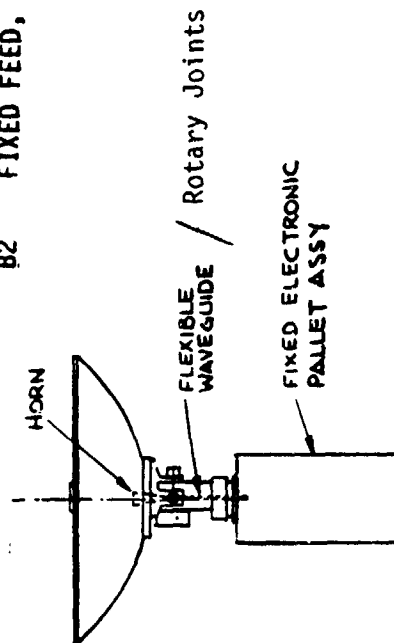
BASELINE TYPE

REFLECTOR/FIXED FEED



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

B2 FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET



B3 FIXED FEED, CASSEGRAIN, FLEXIBLE WAVEGUIDE

B4 FIXED FEED, CASSEGRAIN, ROTARY JOINTS

Mechanical Scanning

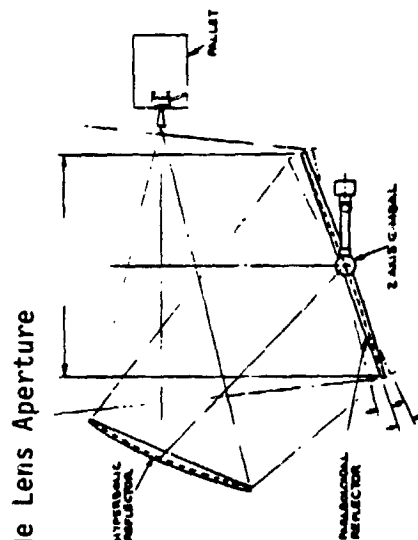
In this second category beam scanning is accomplished by physical movement of a feed against a fixed reflector system (M1) or against a fixed lens (M2) or one reflector is moved against a fixed feed/reflector system (M3 and M4). To improve electrical performance over the scan range dual reflector systems are used (M1 and M3) or a large F/D ratio is used (M2). M4 exhibits performance independent of scan except for physical limitations on the size of the scanned flat reflector. All four configurations are limited to the narrow FOV of TDAS. M1 and M2 (with movable feeds) could accommodate multiple, independently moving feeds thereby providing multiple beams from a single reflector system. The practical implementation, however, is not feasible since feed handover and/or frequency multiplexing would be required whenever two satellite tracks cross-over. As in the first category five independent antenna systems would be required.



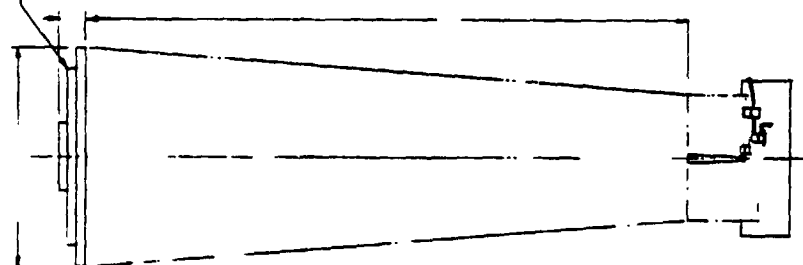
**GENERAL
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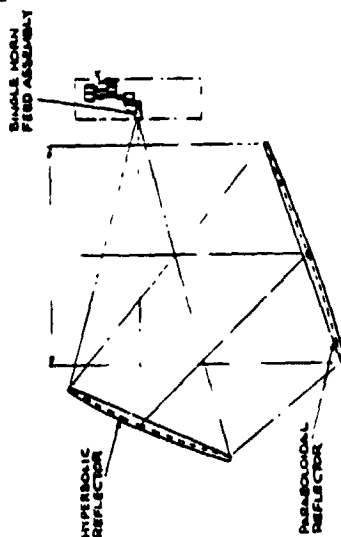
MECHANICAL SCANNING



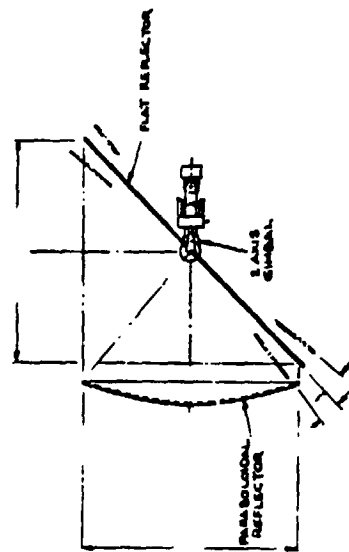
M3 FIXED FEED, DUAL REFLECTOR,
MOVABLE PARABOLOID



M2 MOVABLE FEED, LENS



M1 MOVABLE FEED, DUAL REFLECTOR



M4 FIXED FEED, DUAL REFLECTOR,
MOVABLE FLAT PLATE

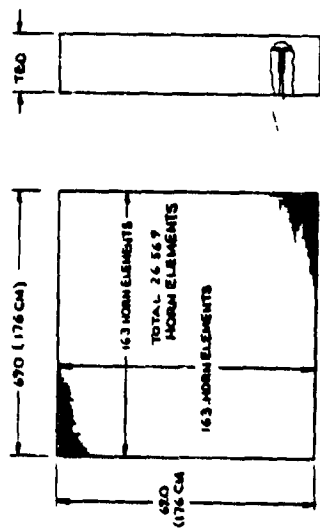
Electronic Scanning

In this third category beam scanning is accomplished exclusively by electronic means. No physical motion of feed or reflector(s) is involved. The configurations include pure phased arrays (E1) and phased array feeds with a fixed dual reflector system for optical magnification (E2) or a multibeam feed system with beamforming network in conjunction with a fixed, dual, folded reflector system. Electronic scanning is limited to the narrow FOV. (A spherical phased array with the potential for a wide FOV was eliminated early in the evaluation because of excessive size and weight.) This third category provides the potential for multiple independent beams from a single aperture. The complexities and attendant performance constraints involved with multiple beam formation are discussed with the various candidates. The special case of a spherical reflector with a phased array feed was eliminated since its performance is inferior to the dual reflector approach of equal size and feed complexity.

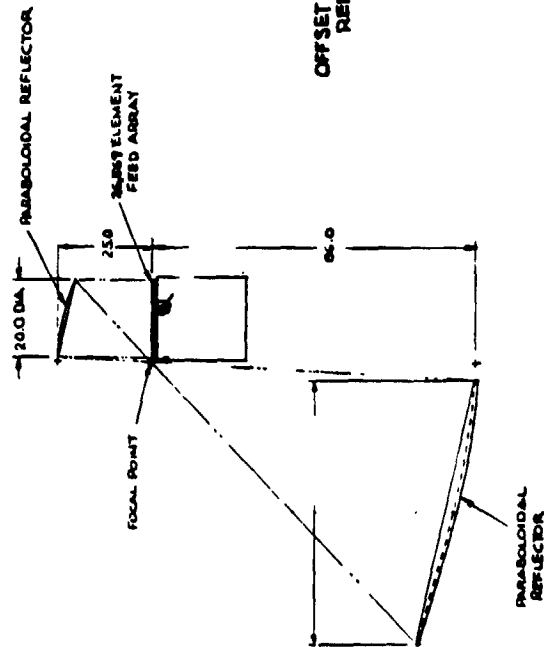


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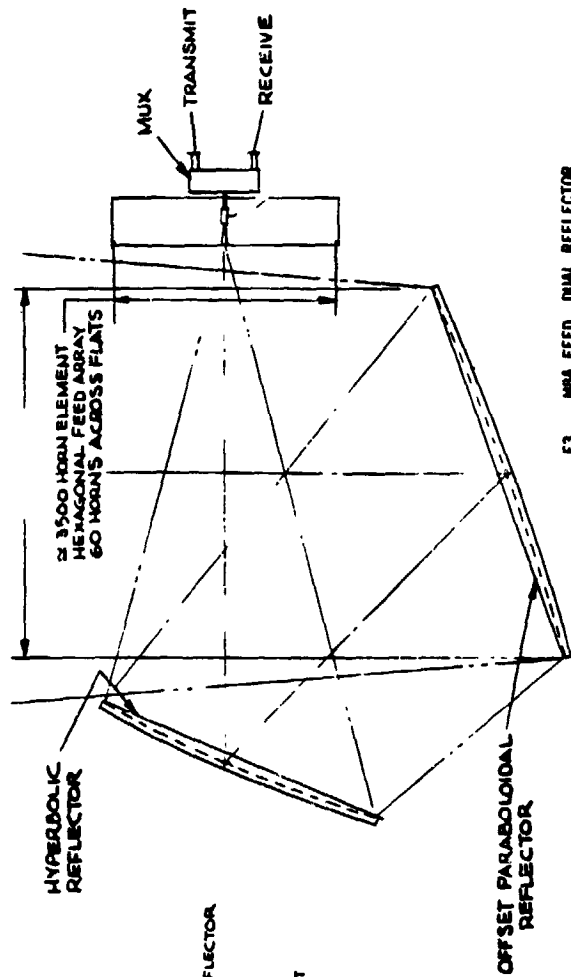
ELECTRONIC SCANNING



E1 PHASED ARRAY



E2 MAGNIFIED PHASED ARRAY, DUAL REFLECTOR



E3 MBA FEED, DUAL REFLECTOR

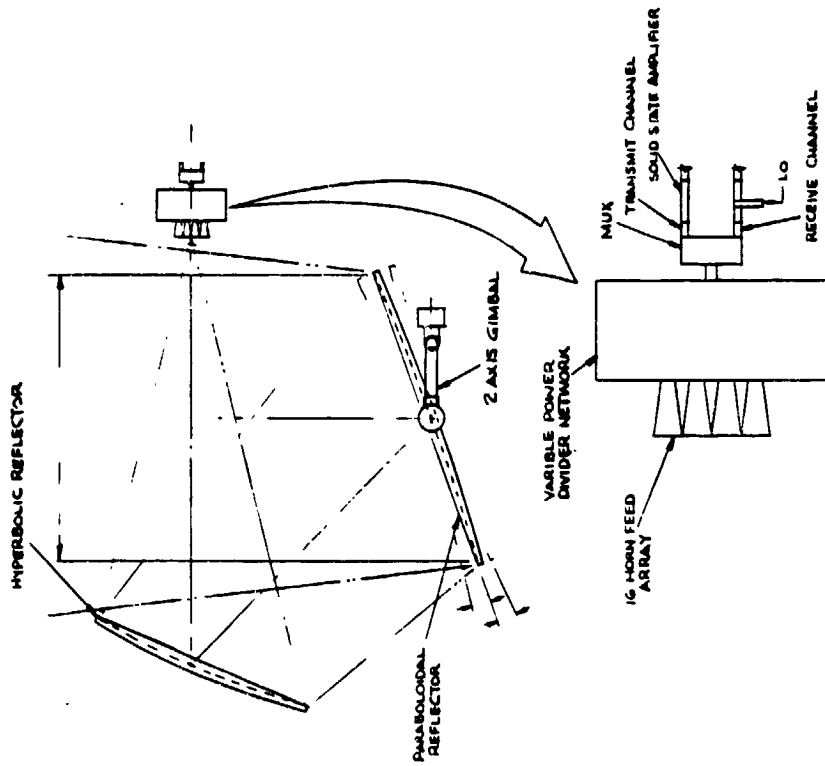
Hybrid/Electronic/Mechanical Scan

This last category combines features of the two previous categories. Beam scanning is basically accomplished by a mechanical scan of a reflector in a dual reflector system such as M3. The resulting optical defocussing is compensated for by a fixed feed array incorporating a variable power divider and phasing network. Again only a limited FOV is available.



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**HYBRID
ELECTRONIC/MECHANICAL
SCANNING**



- H1 ELECTRONICALLY ADJUSTABLE FEED,
DUAL REFLECTOR, MOVABLE PARABOLOID**

3. PHASE A - TRADEOFF RESULTS

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Weighting Factors

The selected performance parameters are not all of equal importance. In order to assign a total score to each configuration we have assigned weighting factors to the performance factors. These range from a low importance of 1 to a maximum importance of 10. The highest being those which are most critical to achieving a successful mission with a system which includes a 60 GHz cross-link. Each of the selected parameters will be defined in order.

- o Reliability: Probability of cross-link providing 10 years service. Includes the internal redundancy of the sub-system. This parameter has the highest rank since all other parameters are unimportant if the sub-system does not survive.
- o Development Risk: The probability that the design can be achieved during the time period of interest. Ranked high because an unobtainable system has no value.
- o Stowage: The stowed volume of the antenna. Rated high since on small S/C or large ones with multiple antennas this parameter largely determines the useability of the antenna.
- o Host S/C Impact: The effects on the S/C of the cross-link antenna except for those which are treated separately. Includes dynamic volume, inertial interaction, platform stability requirements, heat radiated into S/C. Ranked high because it causes penalties and cost at the system level.
- o Loss: Attenuation between receiver input port, transmitter output port and antenna radiating surface. Ranked high since it is a direct measure of the efficiency of the antenna system.
- o Weight/Power: Total sub-system weight and power requirement.
- o Cost: Total sub-system cost exclusive of vehicle integration costs.
- o Integration and System Test Impact: Cost of integrating antenna sub-system with S/C and cost of S/C system level testing of cross-link.
- o Environment Protection: The inherent protection the design provides for the critical receiver, transmitter and antenna control electronics from the environment.
- o Processor Requirements: The complexity of an antenna system dedicated processor.
- o Polarization Purity: The amount of cross-polarization in the beam. Limits the isolation between two signals sharing the same RF-path. Small importance unless a system requires polarization reuse.
- o Beamwidth: Low efficiency antennas must have the aperture enlarged to bring the gain up to 54 db. This results in narrower beamwidth and more difficult tracking and acquisition. Rated low because the variation between antenna types is not large.
- o Sidelobe Levels: Can effect reliability of acquisition and the isolation between multiple antennas. Importance is rated low because sidelobe and isolation effects are temporary and can be overcome by operational measures.
- o Torque Noise: The effect of the acceleration of the moving portion of the antenna system on the spacecraft and payloads with excessive pointing requirements (e.g., laser communication systems).



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WEIGHTING FACTORS



<u>FACTORS</u>	<u>WEIGHT</u>
RELIABILITY	10
DEVELOPMENT RISK	9
STOWAGE	9
HOST S/C IMPACT	8
LOSS	8
WEIGHT	8
POWER	7
COST	5
INTEGRATION AND SYSTEM TEST IMPACT	5
ENVIRONMENT PROTECTION	5
PROCESSOR REQUIREMENTS	3
POLARIZATION PURITY	3
BEAMWIDTH	2
SIDELobe LEVEL	1
TORQUE NOISE	7

Phase A TRADEOFF

Each performance parameter was evaluated on a scale of 5 to 1, one at a time, for each of the antenna configurations. For best performance an individual score of 5 was assigned. For worst performance an individual score of 1 was assigned. Median performance was given a 3 with 2 and 4 given for in-between performance. Each configuration was then given a total score by multiplying the individual performance value by the weighting factor and adding the columns, as shown in the example below for Configuration B1.

Weighting Factors	x	Individual Score	=	Weighted Score
10		4		40
9		3		27
5		3		15
8		5		40
5		5		25
2		5		10
1		5		5
3		5		15
8		5		40
3		4		12
9		5		45
8		5		40
7		5		35
5		5		25
7		3		21
TOTAL				395



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PHASE A TRADEOFF



PERFORMANCE PARAMETER	WEIGHTING FACTOR	BASELINE TYPE REFL.FIXED FEED				MECHANICAL SCANNING				ELECTRONIC SCANNING			HYBRID ELEC/ MECH SCANNING
CONFIGURATION NO.		B1	B2	B3	B4	M1	M2	M3	M4	E1	E2	E3	H1
SYSTEM													
- RELIABILITY	10	4	3	2	3	1	1	4	5	4	3	1	2
- DEVELOPMENT RISK	9	3	3	2	1	1	1	2	5	1	1	1	1
- COST	5	3	2	3	2	1	1	3	4	1	1	1	2
- HOST SPACECRAFT IMPACT	8	5	4	3	2	2	1	2	3	1	1	1	2
- INT. & SYSTEM TEST IMPACT	5	5	2	3	3	3	3	5	5	4	4	4	5
ELECTRICAL													
- BEAMWIDTH	2	5	5	5	3*	2	2	3	5	1	1	1	3
- SIDELOBE LEVEL	1	5	5	5	5	1	1	1	5	2	2	2	3
- POLARIZATION PURITY	3	5	5	5	5	2	2	2	4	1	1	1	3
- LOSS	8	5	5	2	1	2	2	3	5	1	1	1	2
- PROCESSOR REQUIREMENTS	3	4	5	5	5	4	4	4	4	2	2	1	1
MECHANICAL													
- STORAGE	9	5	4	3	2	3	2	3	4	3	2	2	2
- WEIGHT	8	5	4*	5*	5*	4*	2	5*	4	1	1	1	4*
- POWER	7	5	2*	4	4*	4	4	5	5	1	1	1	4*
- ENVIRONMENT PROTECTION	5	5	3	4	4	5	5	5	5	1	1	1	3
- TORQUE NOISE	7	3	1	3	2	4	4	3	3	5	5	5	2
WEIGHTED SCORE		395	298	279	240	234	201	311	392	185	168	143	201

Ranking of Candidates

Designs Suitable For TDAS and User S/C

Only three of the baseline configurations are usable on the user S/C's as well as TDAS because of the scan requirements. B1 the beam waveguide feed/Cassegrain again is the preferred design as shown by the comparative cores.



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**RANKING OF CANDIDATES
DESIGNS SUITABLE FOR TDAS & USER S/C**



<u>RANK</u>	<u>WEIGHTED SCORE</u>	<u>CONFIGURATION #</u>	<u>CONFIGURATION</u>
1	395	B1	BEAM WAVEGUIDE FEED, CASSEGRAIN
2	298	B2	FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET
3	240	B4	FIXED FEED, CASSEGRAIN, ROTARY JOINTS

Ranking of Candidates

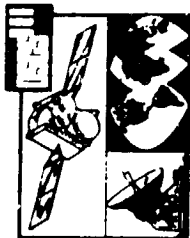
Designs Suitable for TDAS Only

When the requirement is restricted to the limited scan requirement of TDAS a larger number of candidates are available as this list shows. B1 is the best overall candidate although the separation in score is not as large as in the case of candidates that are suitable for user S/C.



SPACE
SYSTEMS
DIVISION

RANKING OF CANDIDATES
DESIGNS SUITABLE FOR TDAS ONLY



<u>RANK</u>	<u>WEIGHTED SCORE</u>	<u>CONFIGURATION #</u>	<u>CONFIGURATION</u>
1	395	B1	BEAM WAVEGUIDE FEED, CASSEGRAIN
2	392	M4	FIXED FEED, DUAL REFLECTOR, MOVABLE FLAT PLATE
3	311	M3	FIXED FEED, DUAL REFLECTOR MOVABLE PARABOLOID
4	298	B2	FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET
5	279	B3	FIXED FEED, CASSEGRAIN, FLEXIBLE WAVEGUIDE

Weight/Power/Volume Comparison

In addition to the weighted overall ranking of the candidates, it is instructive to compare their weight, power requirements and volumes. Weight is a significant factor since some of the candidates that we ranked close together on overall rankings, differ significantly in weight. For example, B2 is 37% heavier than B1 although they are ranked next to each other for TDAS use. Power input is similar for all the candidates except B2 again which requires 40% more than B1 and the phased arrays with their extreme power requirements. The volume requirements are very different for each candidate. In the case of the five candidates marked with an *, which can theoretically provide five simultaneous independent beams, it is worthwhile to compare one of them with five of the single beam designs. Two of the five (M1 and M2) have sufficiently reasonable weights and power requirements to be considered. However, in addition to all the practical problems of implementing these designs, as discussed later in the report, these antennas are more than three times as large as five B1's.



**GENERAL
ELECTRIC**

WEIGHT/POWER/VOLUME COMPARISON



<u>CONFIGURATION</u>	<u>#</u>	<u>WEIGHT (LBS.)</u>	<u>POWER (WATTS)</u>	<u>VOLUME (CU. FT.)</u>
BEAM WAVEGUIDE FEED, CASSEGRAIN	B1	97	59	16
FIXED FEED, CASSEGRAIN, ELECT. PALLET	B2	133	83	30
FIXED FEED, CASSEGRAIN, FLEX WG	B3	101	64	21
FIXED FEED, CASSEGRAIN, ROTARY JOINTS	B4	122	64	56
*MOVABLE FEED, DUAL REF (SINGLE BEAM)	M1	138	64	253 (1)
*MOVABLE FEED, LENS (SINGLE BEAM)	M2	250	64	260 (1)
FIXED FEED, DUAL REF, MOVABLE PARA.	M3	115	59	99
FIXED FEED, DUAL REF, MOVABLE PLATE	M4	125	59	63
*PHASED ARRAY (SINGLE BEAM)	E1	3,660	10,117	59 (2)
*MAGNIFIED PHASED ARRAY, DUAL REF (SINGLE BEAM)	E2	3,639	10,117	169 (2)
*MBA FEED, DUAL REF	E3	325	59+	617 (1)
ELECT. ADJ FEED, DUAL REF, MOVABLE PARA.	H1	167	64	363

+ADDITIONAL POWER OF PHASE SHIFTERS UNDETERMINED AT PRESENT

*THEORETICALLY CAPABLE OF 5 INDEPENDENT BEAMS

(1) ADD 41.7 lbs, 53.6 WATTS AND 2 CU. FT. PER ADDITIONAL BEAM

(2) ADD 421 LBS, 8000 WATTS AND 35 CU. FT. PER ADDITIONAL BEAM

In the following, all 12 candidate antenna systems are described in detail. For each candidate a size comparison is given using the beam waveguide configuration (B1) as a reference. The major strengths (score of 5) and major weaknesses (score of 1) are listed for each system. Also, the loss is discussed and the related aperture size is given as well as estimated weight, power and volume.

- o Weight includes the complete antenna and all fully redundant electronics. The electronics are based on a 1 watt RF transmit output level as outlined in the link budget in Appendix D.
- o Power requirements include the RF electronics, gimbal (where applicable) and control electronics.
- o Volume includes all electronics and the complete antenna including a 26° FOV for gimballed systems.

Configuration B1 - Beamwaveguide Feed/Cassegrain

B1 is the classical beamwaveguide configuration developed and used successfully on large groundstation applications. It is described in more detail in Appendix B. The concept overcomes the limitations of waveguide rotary joints namely, high insertion loss and low power handling capacity. While power handling for wave applications is not demanding (about 1 watt), waveguide insertion loss and especially rotary joint insertion loss becomes prohibitive at 60 GHz. Theoretical attenuation in pure silver waveguide (WR 15) is 0.42 dB/ft. Attenuation in a conventional waveguide rotary joint in the same waveguide size, including required mode transitions and mode filter, is 1.2 dB or 2.4 dB for two rotary joints in a two-axis gimbal. In contrast a two-axis beamwaveguide system can be designed to be nearly loss-free (0.2 dB), practically independent of the separation distance between upper and lower axis. B1 is the clear winner for both narrow and wide FOV applications. The higher total score is due to highest individual scores in most of the heavily weighted parameters such as stowage, host S/C impact, weight, loss and power. It has no major weaknesses (score of 1). Its great advantage is also expressed by the high degree of flexibility and modularity:

- o Various antenna diameters and antenna form factors (F/D, offset geometry) may be used with a given gimbal and support design.
- o The gimbal tower height may be readily varied to accommodate FOV and S/C configuration requirements.
- o The electronic pallet may be inside or outside the S/C envelope, in the latter case adding to the tower weight.
- o Interfaces between antenna/gimbal/electronics are simple and flexible.

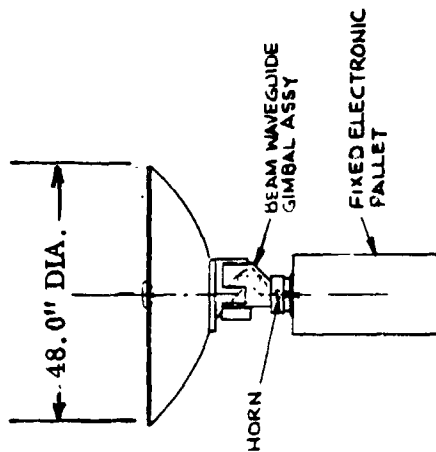
Preliminary studies indicate a hemispherical field of view, i.e. $\pm 90^\circ$, is feasible with an aperture diameter of ≈ 3.0 ft. This decreases to $\approx \pm 75^\circ$ with a 5.0 ft aperture diameter. This is due to the interference between the reflector and the gimbal assembly, and depends on aperture F/D, diameter, gimbal size, and pallet structure configuration.



**GENERAL
ELECTRIC**

B1

BEAM WAVEGUIDE FEED, CASSEGRAIN



MAJOR STRENGTHS	WEIGHT
Usable TDAS & User	-
Stowage	9
Host S/C Impact	8
Weight	8
Loss	2
Power	7
Integration & System Test Impact	5
Environment Protection	5
Polarization Purity	3
Beamwidth	2
Sidelobe Levels	1

MAJOR WEAKNESSES	WEIGHT
None	-

WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
97	59	16

TOTAL SCORE

395

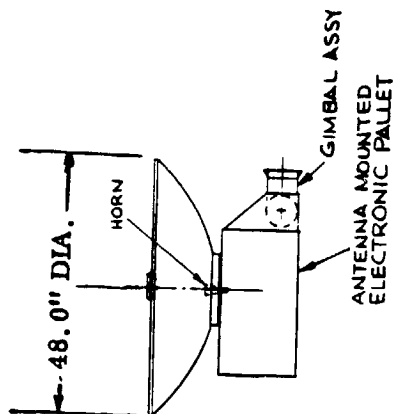
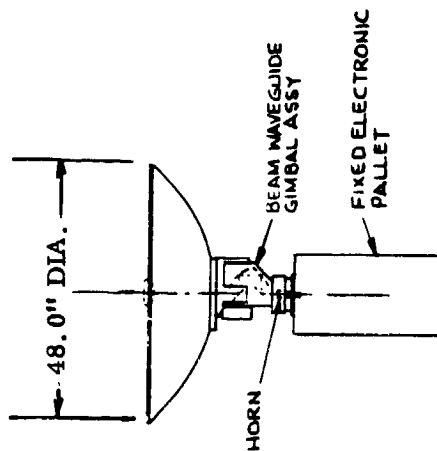
Configuration B2 - Fixed Feed/Cassegrain/Electronics Pallet

In this configuration all the mm wave components are contained in the pallet that is fixed mounted to the reflector. Here the beamwaveguide gimbal assembly with its small loss is eliminated, but the aperture remains practically the same. The size comparison figure is somewhat misleading since it does not show the increase in swept volume as a result of the motion of the antenna mounted pallet.



**GENERAL
ELECTRIC**

SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

B2 FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET

Configuration B2 - Fixed Feed/Cassegrain/Electronics Pallet

B2 scores considerably lower and ranks 4th. Its only important major strength is the low loss. Again there are no major weaknesses and weight and power compare well with B1. With the electronics unprotected by the S/C envelope and illuminated by the sun from all sides while scanning this configuration requires a complex, multi-dimensional heat pipe temperature control system to insure low noise-figure receiver performance. This has a severe negative impact on both system integration and test and hence cost. In terms of functional electrical performance B2 equals B1 and the comments made on modularity and flexibility apply equally here.

The processed signal transmission lines must go through the two gimbal axes on route to the spacecraft electronics. They must flex or be provided with rotary joints to withstand the orbital life requirements. The gimbal location on the pallet, as shown, will cause center of gravity motion of the antenna assembly during slewing, which would have an increased effect on spacecraft pointing.



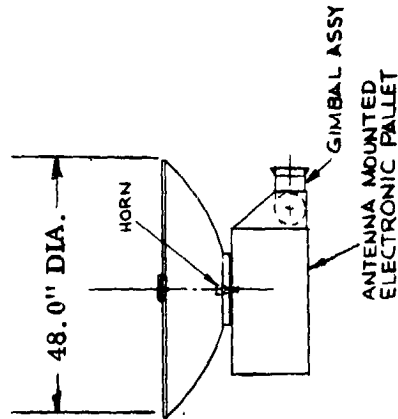
**GENERAL
ELECTRIC**

B2

FIXED FEED, CASSEGRAIN, ELECTRONICS PALLET



MAJOR STRENGTHS	WEIGHT
Usable TDAS & User	-
Loss	8
Processor Requirements	3
Polarization Purity	3
Beamwidth	2
Sidelobe Level	1



MAJOR WEAKNESSES	WEIGHT
None	-

WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
133	83	30

TOTAL SCORE

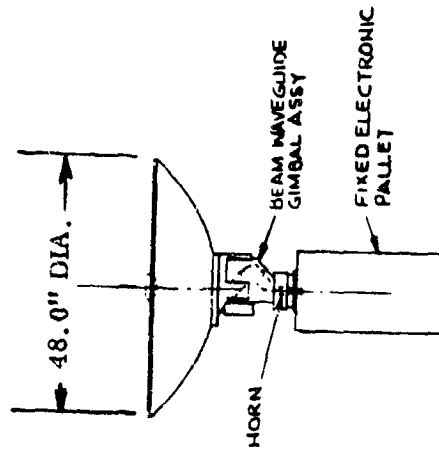
298

Configuration B3 - Fixed Feed/Cassegrain/Flexible Waveguide

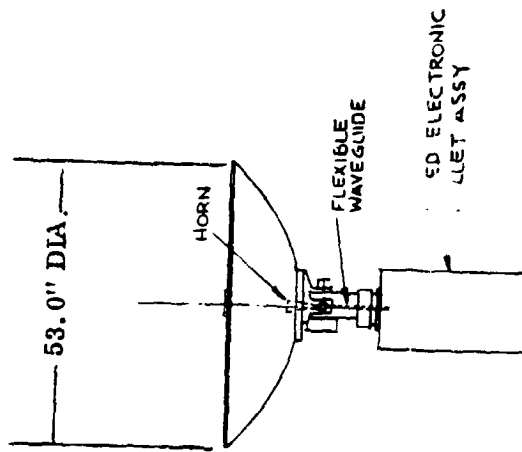
In this configuration the beamwaveguide of B1 is replaced by flexible waveguide. The flex angle/lifetime of this joint is a function of the length of the flexible waveguide. In a practical sense this configuration is limited for TDAS application only ($\pm 13^\circ$ FOV). A 0.8 dB additional insertion loss was assumed for this flexible waveguide forcing a 10% increase in aperture diameter.



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN



B3 FIXED FEED, CASSEGRAIN, FLEXIBLE WAVEGUIDE

Configuration B3 - Fixed Feed/Cassegrain/Flexible Waveguide

The flexible waveguide approach appears like a straightforward, simple solution for a narrow FOV application. However, the detailed evaluation results in low scores for many important parameters. Reliability is largely unknown and development efforts have so far been less than successful. Additional effort during Phase B is required to provide a better assessment of the industry state-of-the-art. Development risk and cost are equally uncertain and require further study. An acceptable penalty in electrical performance is the additional flexible waveguide loss which can be recovered by an increase in antenna aperture at relatively little cost in weight and power. The implementation of a monopulse type autotrack system however, leads to great complexity. Parallel flexible waveguides are now required or monopulse error signal processing must be accomplished in an environmentally controlled pallet mounted to the reflector. Transmit/Receive signal stability and monopulse accuracy would be critically affected by multiple flexible waveguides. It also becomes clear that design modularity and flexibility is greatly reduced by a complex interface situation.



**GENERAL
ELECTRIC**

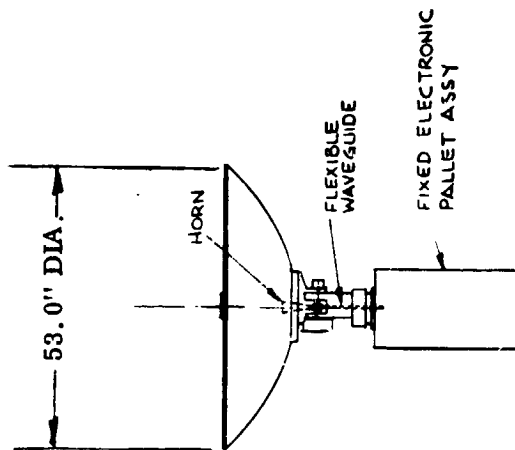
B3

FIXED FEED, CASSEGRAIN, FLEXIBLE WAVEGUIDE



<u>MAJOR STRENGTHS</u>	<u>WEIGHT</u>
Polarization Purity	3
Processor Requirements	3
Beamwidth	2
Sidelobe Level	1

<u>MAJOR WEAKNESSES</u>	<u>WEIGHT</u>
Usable TDAS Only	-



<u>WEIGHT (LBS)</u>	<u>POWER (W)</u>	<u>VOLUME (FT³)</u>
101	64	21

TOTAL SCORE

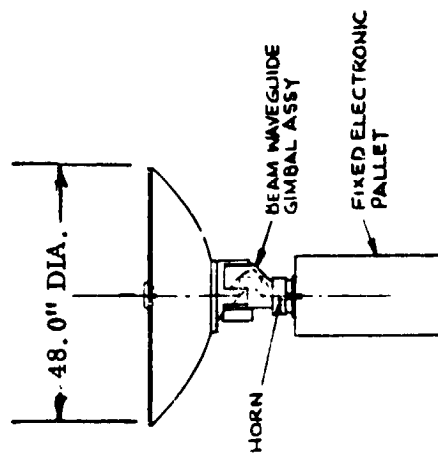
2/9

Configuration B4 - Fixed Feed/Cassegrain/Rotary Joints

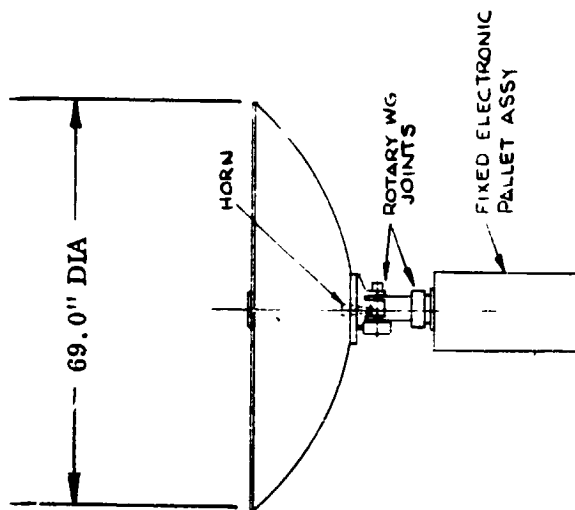
Configuration B4 replaces the flexible waveguide of B3 with rotary joints, one for each axis, providing the large FOV required for user application. The penalty as discussed above is insertion loss: two rotary joints (2.4 dB) and additional interconnecting waveguide (0.8 dB) result in 3.2 dB insertion loss. To recover this loss the antenna diameter has to be increased by a factor of 1.45 (69" instead of 48" for B1).



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN



B4 FIXED FEED, CASSEGRAIN, ROTARY JOINTS

Configuration B4 - Fixed Feed/Cassegrain/Rotary Joints

The increased aperture produces a severe ripple effect into weight, power and swept volume (especially for the full FOV). The monopulse complexity is similar to B3, but stacking of multiple rotary joints is feasible.

It is important to note, however, that for links with a more modest data rate requiring less antenna gain the lossy rotary joint solution may be very acceptable. This is especially true for the case where the antenna beamwidth has increased to a value where command pointing becomes feasible and monopulse tracking is no longer required.

To achieve the specified antenna gain of 54 dB it would be very important to improve the rotary joint loss performance. Further effort will be applied in Phase B to investigate this potential. For the present evaluation loss and development risk are considered major weaknesses.



**GENERAL
ELECTRIC**

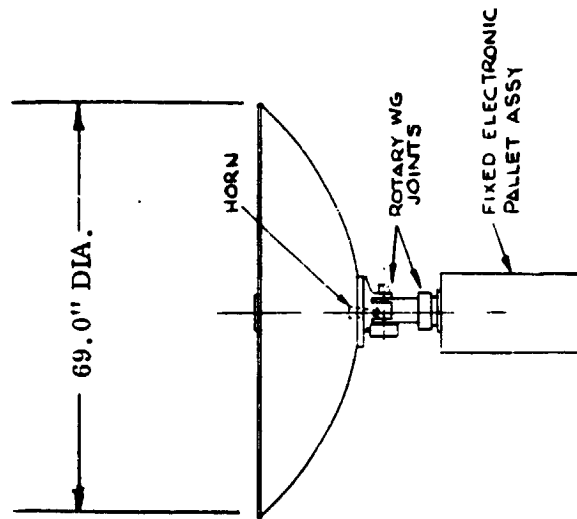
B4

FIXED FEED, CASSEGRAIN, ROTARY JOINTS



MAJOR STRENGTHS	WEIGHT
Usable for TDAS & User	-
Polarization Purity	3
Processor Requirements	2
Sidelobe Level	1

MAJOR WEAKNESSES	WEIGHT
Development Risk	9
Loss	8



WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
122	64	56

TOTAL SCORE

240

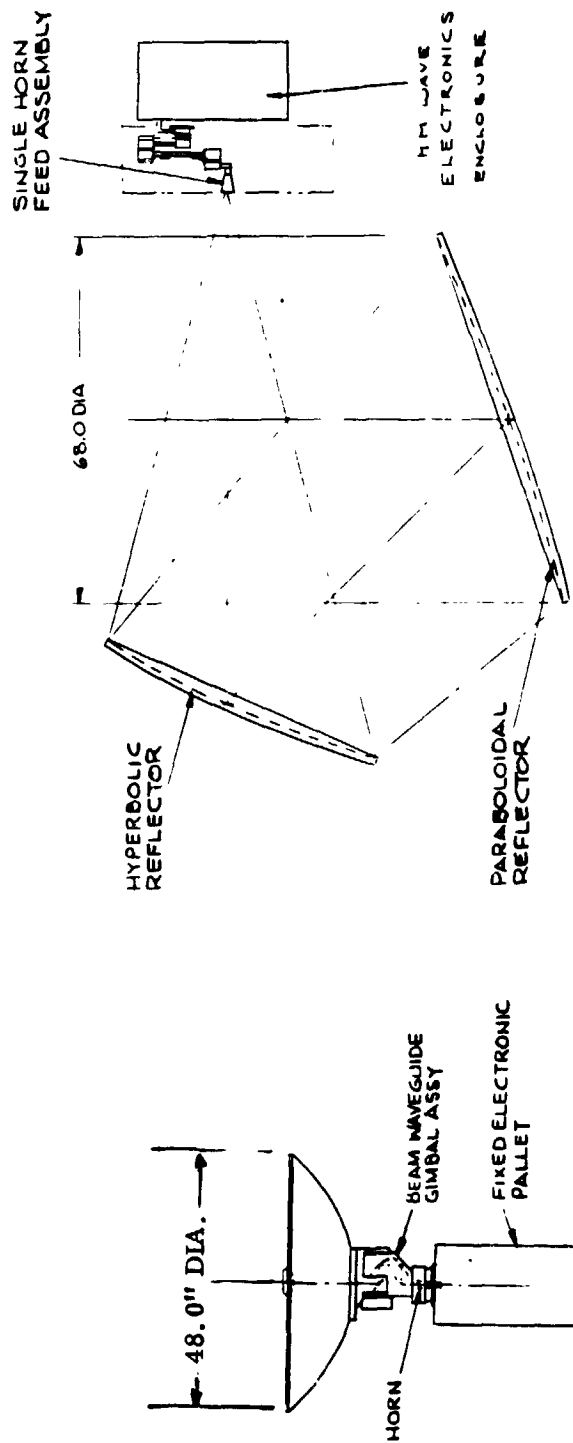
The following four configurations M1 to M4 are mechanical scan types. It must be pointed out that for all the mechanical scan systems, except for M4, there is a beam distortion that increases with scan angle. If any of these configurations are selected for further study, the effect of this distortion on the monopulse autotrack performance must be examined. For example, the use of a single horn TE₂₁ mode attitude sensor might be less attractive than it appears for the baseline approaches. For the hybrid configuration (H1), a multihorn sensor might be considered, but distortion effects might be serious in that case, as well.

Configuration M1 - Moveable Feed, Dual Reflector

The combined loss of the rotary joints and of the $\pm 13^\circ$ beam scan is optimistically assessed at 3 dB, increasing the required aperture of the paraboloid reflector from 48" to 68".



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

M1 MOVABLE FEED, DUAL REFLECTOR

Configuration M1 - Movable Feed, Dual Reflector

This configuration would require a feed positioning mechanism that would border on being impractical. Not only does the feed horn have to be positioned in two orthogonal directions, it must also be tilted in angle for each particular position to minimize spill over losses. The rotary joints and waveguide losses would certainly be excessive penalties to pay for the use of this concept. In addition, two large precision reflector surfaces are required instead of one which adds to the complexity of an already complicated concept.

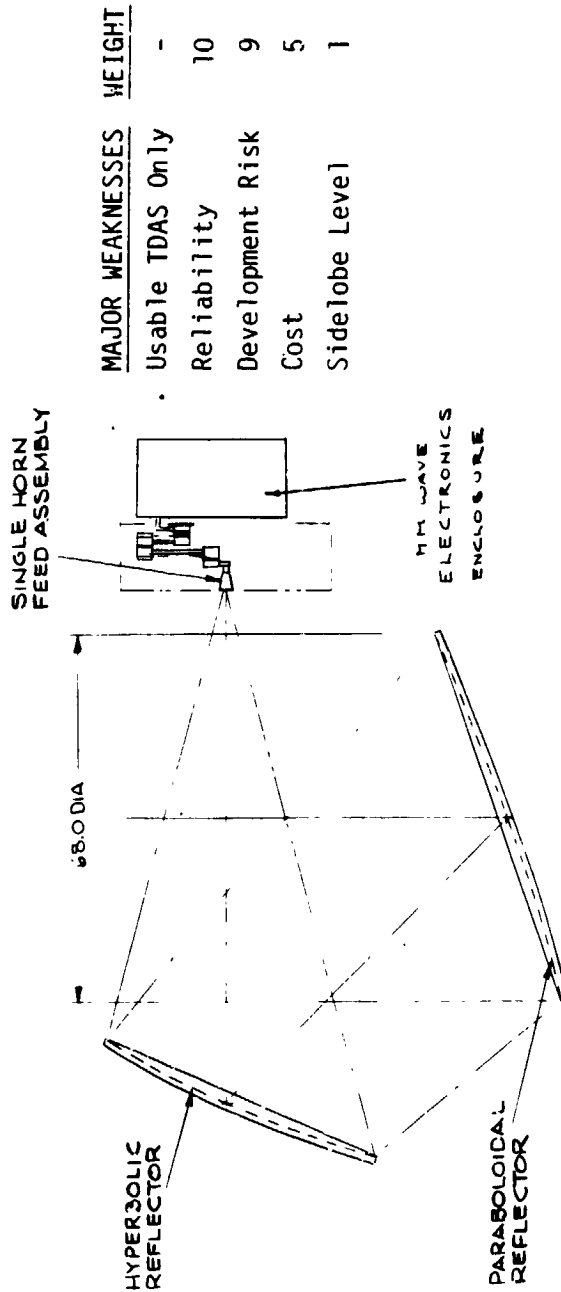
The dual reflector folded optics provides the equivalent of a very large F/D ratio (F/D - 5) and keeps the scan loss to less than 1/2 dB.



**GENERAL
ELECTRIC**

M1

MOVABLE FEED, DUAL REFLECTOR



MAJOR STRENGTHS	WEIGHT
Environment Protection	5

MAJOR WEAKNESSES	WEIGHT
Usable TDAS Only	-
Reliability	10
Development Risk	9
Cost	5
Sidelobe Level	1

51

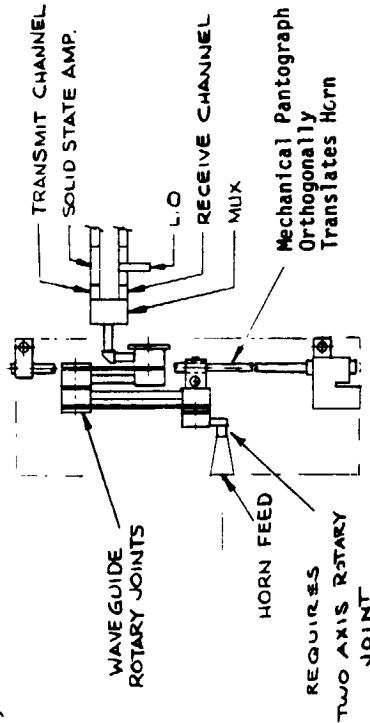
WEIGHT (LBS) 138

POWER (W) 64

VOLUME (FT³) 253

TOTAL SCORE

234



HORN FEED AND TRANSPORT
MECHANISM

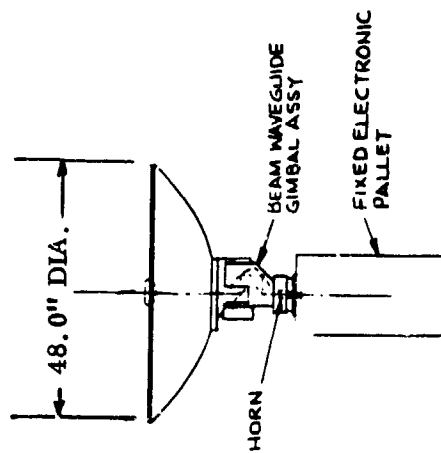
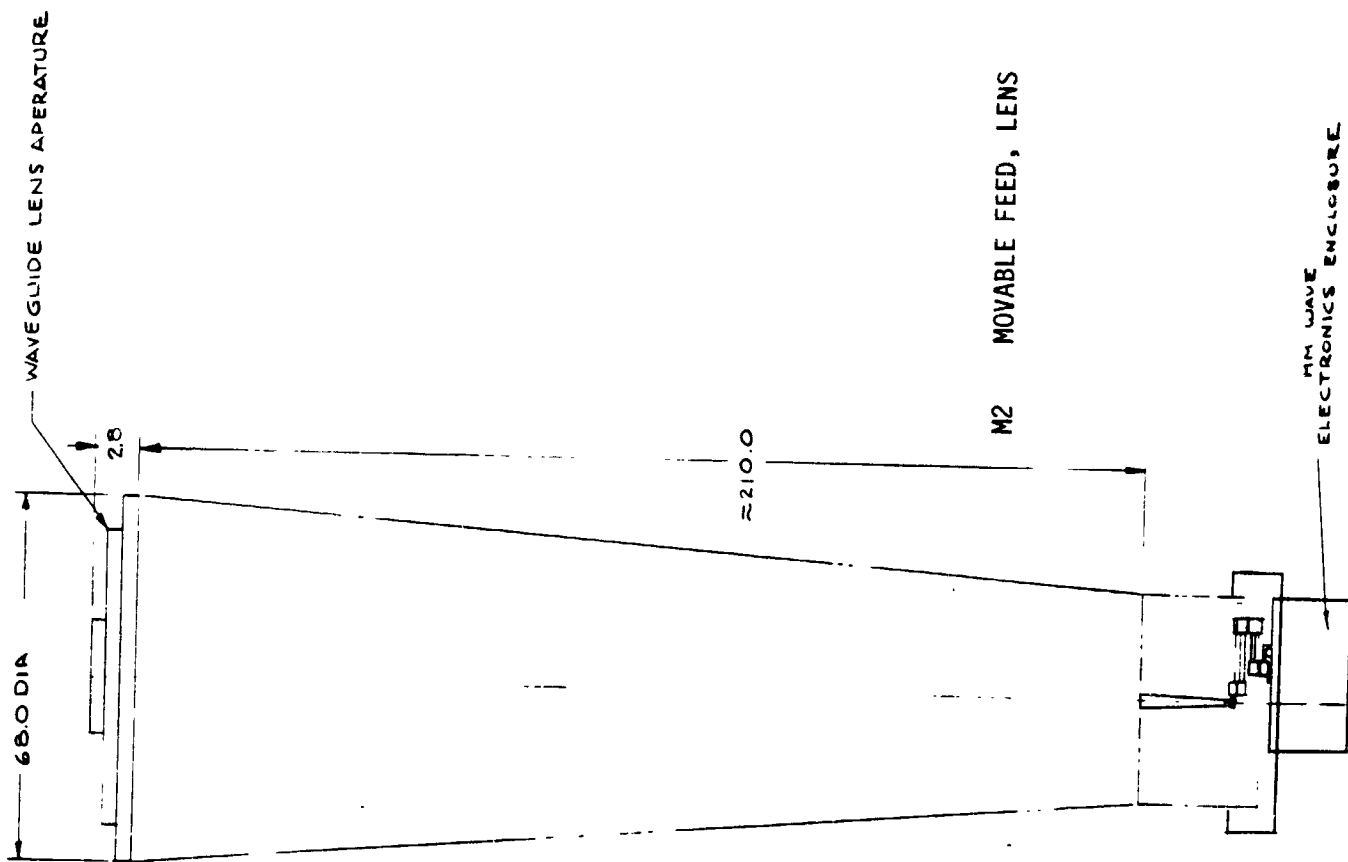
Configuration M2 - Movable Feed, Lens

This waveguide lens approach is dimensioned for comparable performance to M1. Both aperture diameter and focal length are becoming excessive.



**GENERAL
ELECTRIC**

SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

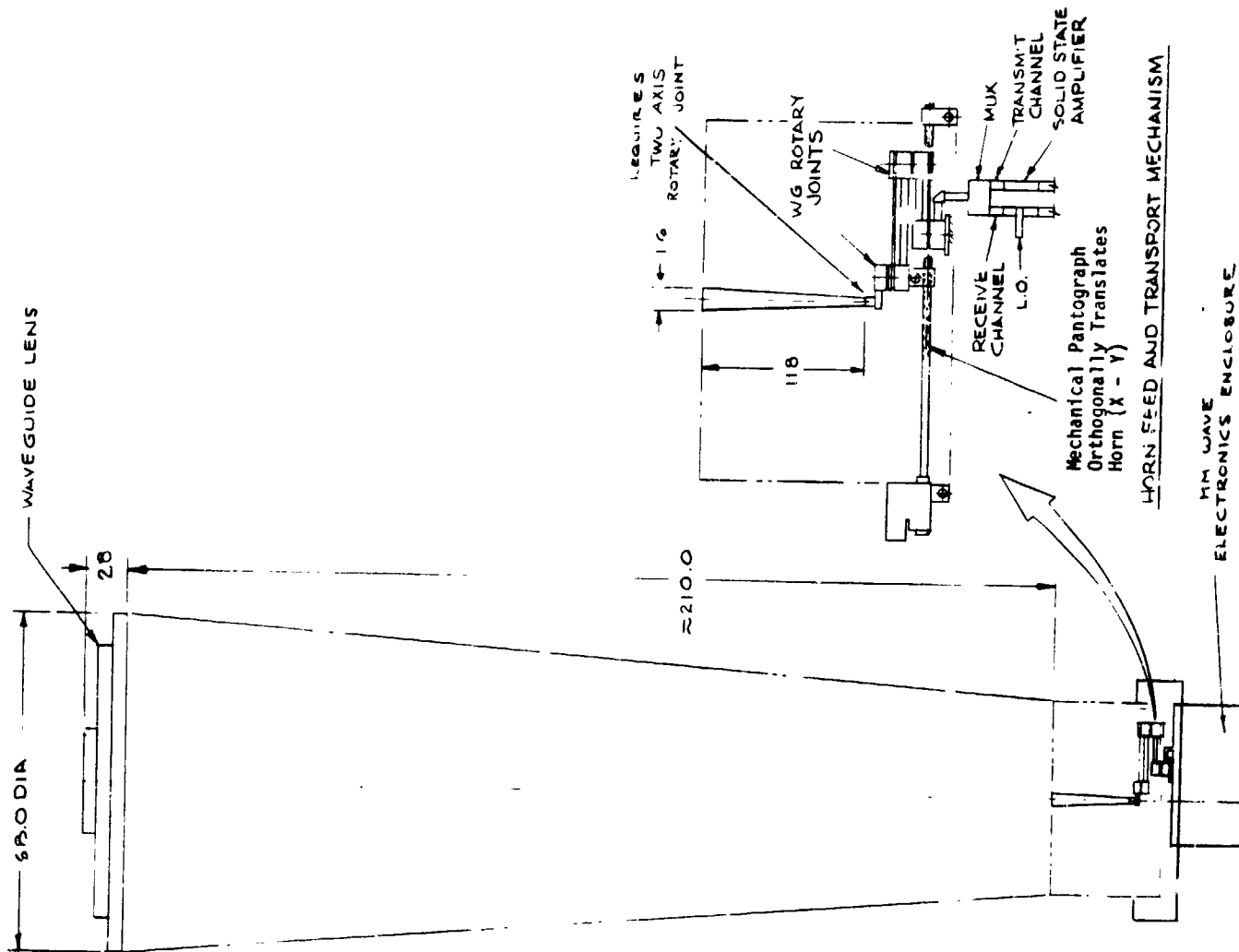
Configuration M2 - Movable Feed, Lens

This configuration contains all the disadvantages of the M1 concept for the horn feed and transport mechanism. In addition, its total length and volume make this concept impractical for spacecraft integration.



**GENERAL
ELECTRIC**

**M2
MOVABLE FEED, LENS**



MAJOR STRENGTHS		WEIGHT
Environment Protection		5
MAJOR WEAKNESSES		WEIGHT
Usable TDAS Only		-
Reliability		10
Development Risk		9
Host S/C Impact		8
Cost		5
Sidelobe Level		1

WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
250	64	260

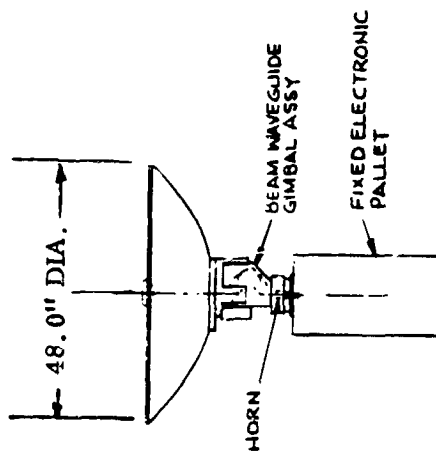
**TOTAL SCORE
201**

Configuration M3 - Fixed Feed, Dual Reflector, Movable Paraboloid

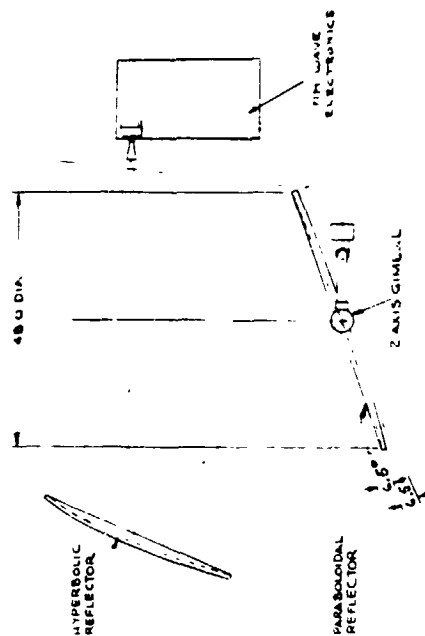
This fixed feed concept without rotary joints is quite efficient. The large equivalent focal length of the folded optics keeps the scan loss small and the projected aperture remains at 48". The gimballed paraboloid reflector is elliptical in contour, approximately 61" x 53".



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN



M3 FIXED FEED, DUAL REFLECTOR,
MOVABLE PARABOLOID

Configuration M3 - Fixed Feed, Dual Reflector, Movable Paraboloid

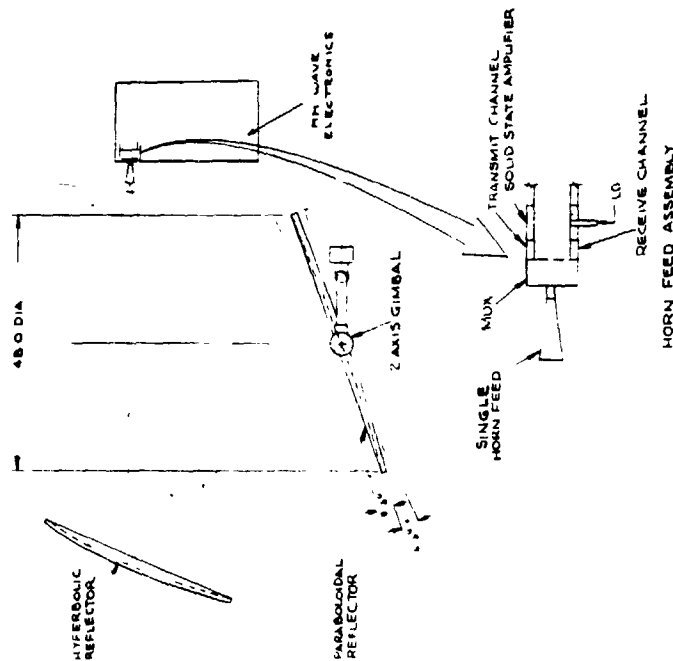
This configuration requires two large precision reflector surfaces and support structure to support them and maintain alignment. In addition, its geometry prohibits large FOV capability, and requires a large stowage volume for spacecraft integration.



**GENERAL
ELECTRIC**

M3

**FIXED FEED, DUAL REFLECTOR
MOVABLE PARABOLOID**



MAJOR STRENGTHS	WEIGHT
Power	7
Environment Protection	5
Integration & System Test Impact	5

MAJOR WEAKNESSES	WEIGHT
Usable TDAS Only	1
Sidelobe Level	1

WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
115	59	99

TOTAL SCORE

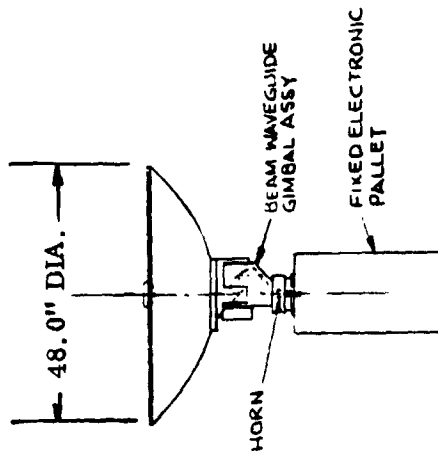
311

Configuration M4 - Fixed Feed, Dual Reflector, Movable Flat Plate

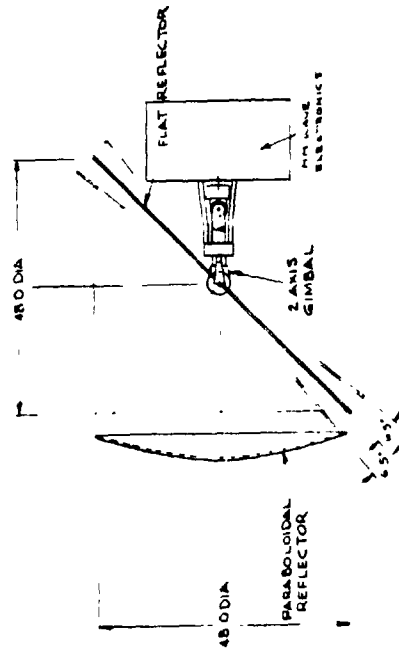
As for M3 the projected aperture remains at 48", whereas the gimballed flat reflector, nominally positioned at 45°, is elliptical in contour, measuring approximately 75" x 53".



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN



M4 FIXED FEED, DUAL REFLECTOR,
MOVABLE FLAT PLATE

Configuration M4 - Fixed Feed, Dual Reflector, Movable Flat Plate

A fixed (deployed) paraboloid reflector and a fixed feed are used to form the beam which is then reflected by the flat reflector mounted on the 2-axis gimbal. Moving the flat reflector by 1° deflects the beam by 2° so that a gimbal angle of only $\pm 6.5^\circ$ provides the required beam scan of $\pm 13^\circ$. If the flat reflector is made large enough--simulating an infinite flat plane--no beam degradation with scan is experienced.

This is an attractive candidate with proven performance on the MIT Lincoln Lab LES 8/9 satellites. However the configuration requires two precision reflector surfaces (one of which is flat), a deployment mechanism for the reflectors and 2-axis gimbal and hence a rather large stowage volume.



GENERAL
ELECTRIC

M4

FIXED FEED, DUAL REFLECTOR
MOVABLE FLAT PLATE



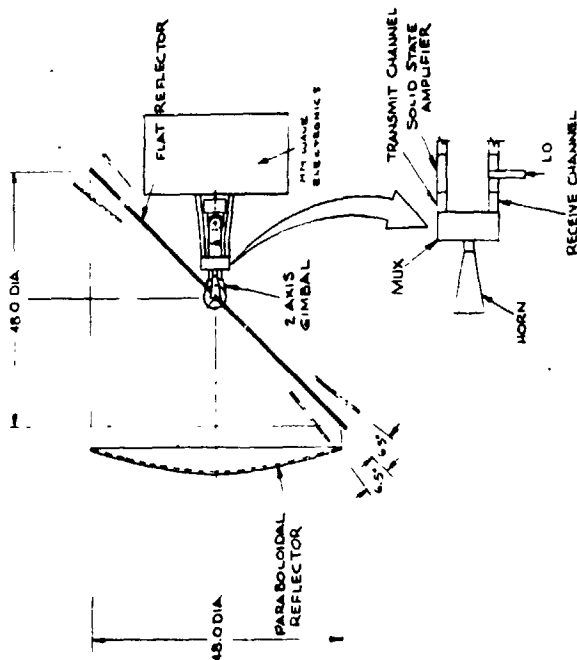
MAJOR STRENGTHS WEIGHT

Reliability	10
Development Risk	9
Loss	8
Power	7
Environment Protection	5
Integration & Sys. Test Impact	5
Beamwidth	2
Sidelobe Level	1

93

MAJOR WEAKNESSES WEIGHT

Usable TDAS Only -
None



HORN FEED ASSEMBLY

WEIGHT (LBS) POWER (W) VOLUME (FT³)

125 59 63

TOTAL SCORE

392

The following three configurations E1 to E3 are electronic scan type...

Configuration E1 - Phased Array

As described in Appendix A, the large size of this array is driven by the attempt to achieve 54 dB of peak gain over the coverage area with a single transmit/receive aperture with shared phase shifters. If separate transmit and receive apertures are used, the size of each aperture can be substantially reduced.

For the transmit phased array, the phase shifter (with a loss of 3 dB - See Figure 4 of Appendix A) can be moved to the low power side of the amplifier, the filter requirements would be substantially eased resulting in about 0.2 dB loss, and no circulator (0.2 dB loss) is needed. This reduction of 4.0 dB of loss between the amplifier output and the horn element means that a transmit array of about 10,000 elements would be adequate (44" x 44"). For the receive array, the phase shifter must still be between the horn and the summing network to avoid the requirement for thousands of mixers, low noise amplifiers, and a means of generating thousands of coherent mm L0 signals (i.e. generating 10 W at 40 GHz and dividing it 12,600 ways with a low loss waveguide power divider). The phase shifter can be a ferrite, non-reciprocal device, however, with only 1.0 dB of loss. The receive array could be realized with about 12,600 horns (48" x 48"). Thus by using separate transmit and receive arrays, the total number of horns required would be reduced by about 15%. The DC to RF efficiency would be increased 2.5 times, the antenna beamwidth would increase by 63%, and thermal and mechanical assembly problems would be eased. The implications of multibeam operation from a single array are discussed in Appendix A.

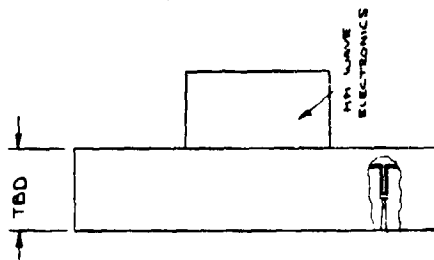
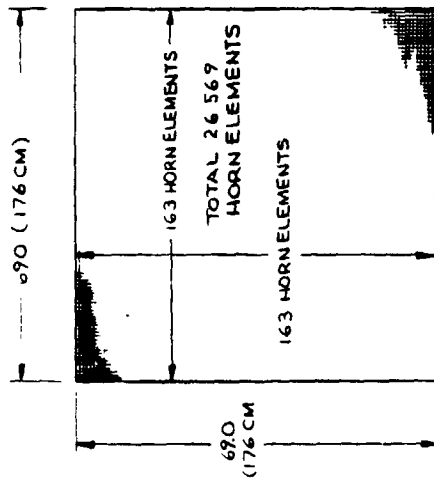
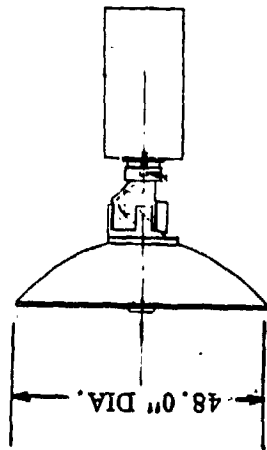


GENERAL
ELECTRIC

SIZE COMPARISON



SPACE SYSTEMS DIVISION



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

E1 PHASED ARRAY

Configuration E1 - Phased Array

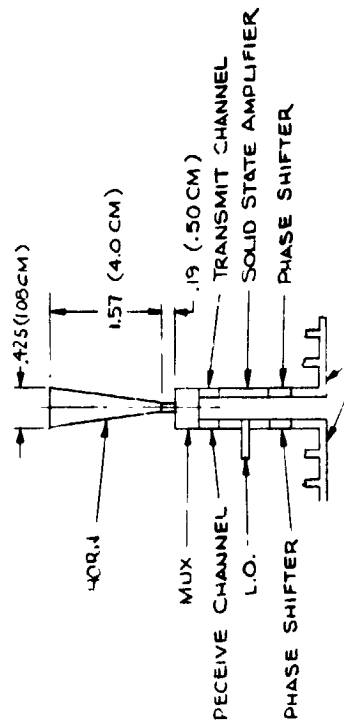
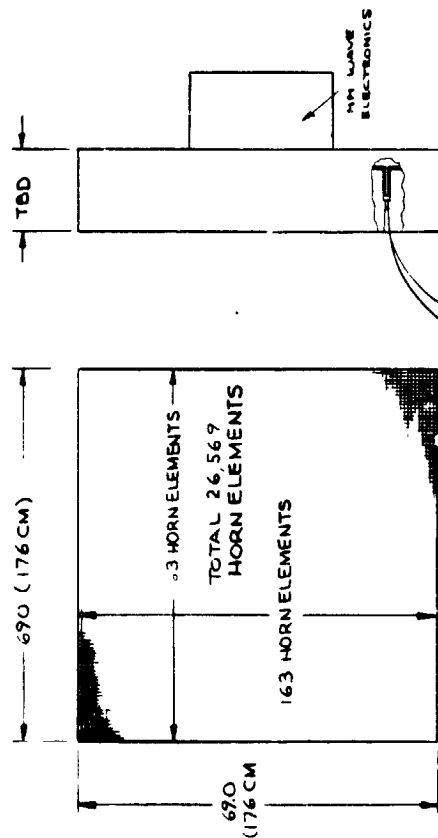
The list of major weaknesses speaks for itself. The large number of elements to provide 54 dB of gain over a scan angle of $\pm 13^\circ$ is an overwhelming disadvantage which cannot be made up by the two advantages of beam agility and inertia-free beam scan.

One other factor must be considered in the use of a phased array. The power consumed by the phase shifter and its associated circuitry. At the present state-of-the-art, diode 5 bit phase shifters require about 100 mw of continuous power. Not only must provision be made to supply the required 2 to 3 kw of power per array but the thermal problem arising from the phase shifters would exceed that of the amplifiers and would require a large dedicated radiator area. Using separate arrays for transmit and receive with non-reciprocal, latching ferrite phase shifters eliminates the problem of high average power but high peak power is still required for the phase shifters.



**GENERAL
ELECTRIC**

E1 PHASED ARRAY



SUMMING NETWORK

WEIGHT (LBS)	POWER (W)	VOLUME (FT ³)
3660	10,117	59

TOTAL SCORE
185

MAJOR STRENGTHS
None

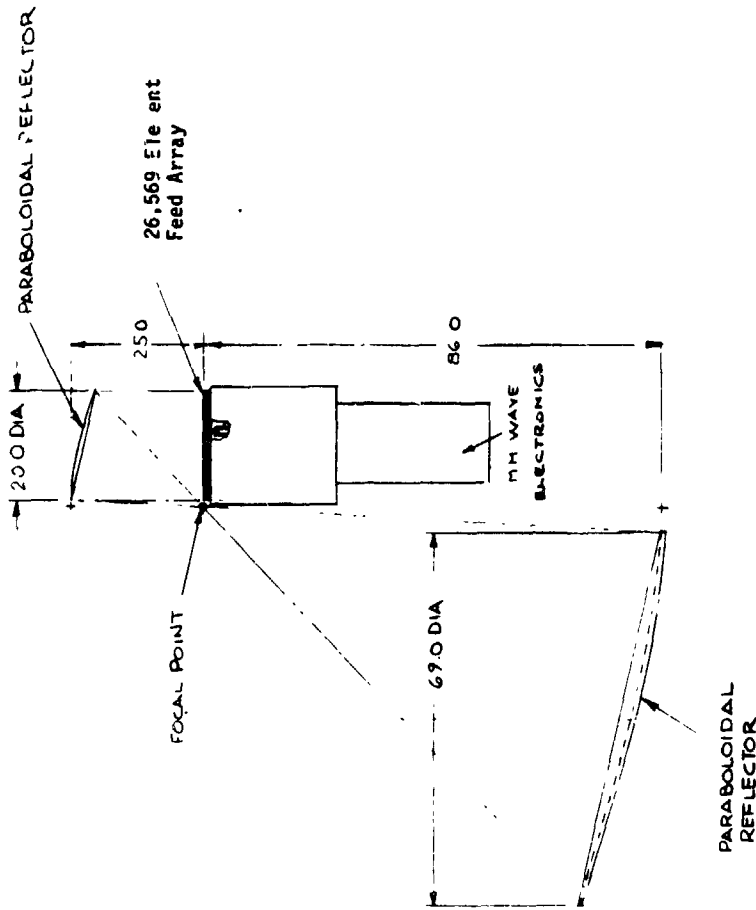
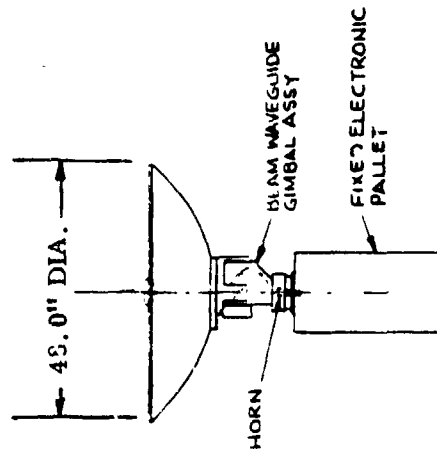
MAJOR WEAKNESSES	WEIGHT
Usable TDAS Only	-
Development Risk	10
Loss	8
Weight	8
Host S/C Impact	8
Power	7
Cost	5
Environment Protection	5
Polarization Purity	3
Beamwidth	2

Configuration E2 - Magnified Phased Array

In a magnified phased array, the magnified image of a reduced size array appears in the aperture plane of large paraboloid¹. The size of this image, and thus the size of the large paraboloid, is defined by the size of an unmagnified array that can meet the performance requirements. This size was determined for configuration E1 as a 69" square. For this reason as well as those discussed in the next paragraph, the 69" diameter shown in the figure is probably too small.



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

E2 MAGNIFIED PHASED ARRAY, DUAL REFLECTOR

Configuration E2 - Magnified Phased Array

The use of dual confocal paraboloids as shown (or lens arrangements) have been studied¹, 2 as a means to "magnify" a small (low gain) array so as to function as a larger (higher gain) phased array. This approach offers little for the present application.

The magnified phased array is subject to all the limitations and restrictions as the basic phased arrays previously discussed. For example, for a perfect optical system the same number of components would be required but each feed horn aperture might be reduced in size by a factor of 3, at a cost of two precision reflectors and increasing the required scanning angle by three. The smaller feeds and wider scan angles will lead to serious mutual coupling problems. In addition, the optics are not perfect². Spill-over and scan distortions, especially in the plane of symmetry, would require an increase in the number of elements over that of the basic phased array to overcome the gain loss. Studies have shown² that for the same beamwidth, only a few degrees of scan are possible without substantial scan loss (i.e., for a magnification of 3 and a scan of 2.3 degrees about 8 db of scan loss can be expected). No practical way of achieving 13 degrees of scan with 54 db of edge of scan gain can be seen at present with this method.

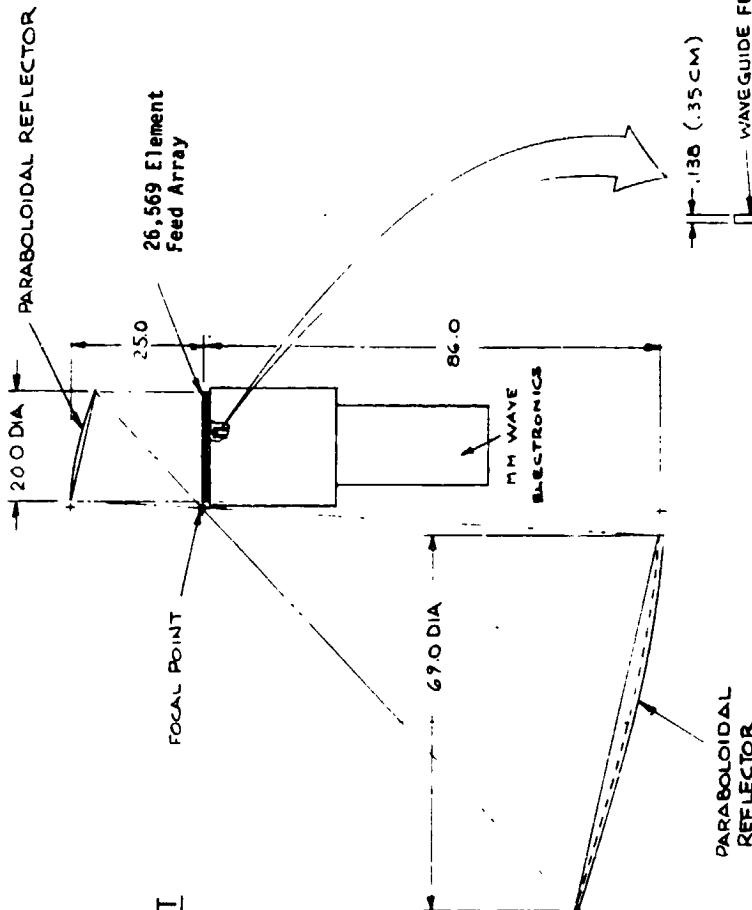
1. "Imaging Reflector Arrangements to Form a Scanning Using a Small Array", by C. Dragone and M. J. Gans, the BELL SYSTEM TECHNICAL JOURNAL, Vol. 58, No. 2, Feb. 1979, pp. 501-515.
2. "Phased-Array-Fed Antenna Configuration Study", by R.M. Sorbello, A.I. Zaghoul, B.S. Lee, S. Siddiqi, B.D. Geller, COMSAT LABORATORIES, Final Report, submitted to NASA Lewis Research Center, Oct. 1983. Contract No. NAS3-23250, Report Nos. CR 168231/2.



GENERAL
ELECTRIC

E2

MAGNIFIED PHASED ARRAY, DUAL REFLECTOR



MAJOR STRENGTHS WEIGHT
None -

MAJOR WEAKNESSES WEIGHT
Usable TDAS Only -
Development Risk 9
Loss 8
Weight 8
Host S/C Impact 8
Power 7
Cost 5
Environment Protection 5
Polarization Purity 1
Beamwidth 1

WEIGHT (LBS) POWER W VOLUME (FT³)
3,639 10,117 169

TOTAL SCORE

163

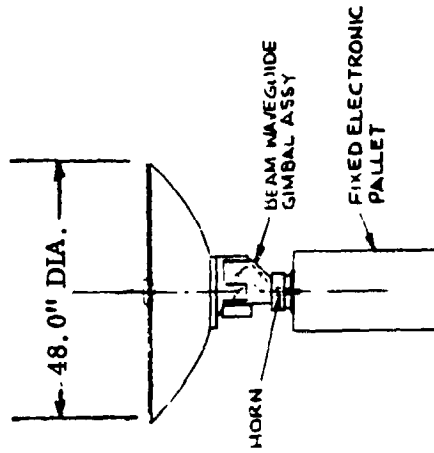
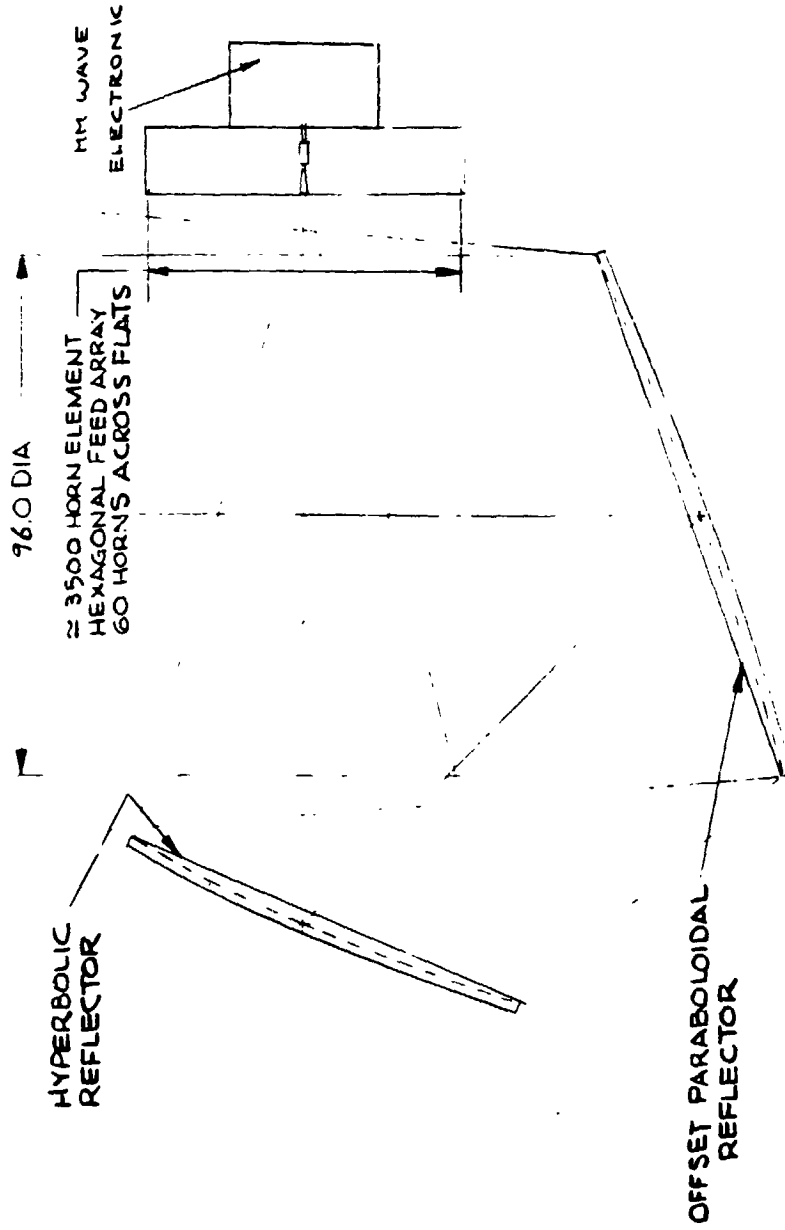
FEED ELEMENT ASSEMBLY

Configuration E3 - MBA Feed, Dual Reflector

The large aperture size of this configuration is driven by the minimum gain required in conjunction with all the loss mechanisms as described in Appendix A.



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

E3 MBA FEED, DUAL REFLECTOR

Configuration E3 - MBA Feed, Dual Reflector

The MBA was examined in the proposal and in greater depth in Appendix A. It can be seen that the two very large precision reflectors along with thousands of feeds and the complex beam forming network results in a system with nothing to recommend it. It also depends upon the development of a reciprocal, low loss variable power divider and phase shifter which does not yet exist at 60 GHz.



**GENERAL
ELECTRIC**

**HYPERBOLIC
REFLECTOR**

E3

MBA F³ DUAL REFLECTOR

10 DIA

≈ 3500 HORN ELEMENT
HEXAGONAL FEED ARRAY
60 HORNS ACROSS FLATS

MM WAVE
ELECTRONICS

MAJOR STRENGTHS

None

WEIGHT



SPACE SYSTEMS DIVISION

MAJOR WEAKNESSES

WEIGHT

Usable TDAS Only

Reliability

Development Risk

Weight

Loss

Host S/C Impact

Power

Environment
Protection

Cost

Polarization Purity

Processor
Requirements

Beamwidth

-

10

9

8

8

8

7

5

5

3

3

2

**OFFSET PARABOLOIDAL
REFLECTOR**

WEIGHT (LBS)

325

POWER (W)

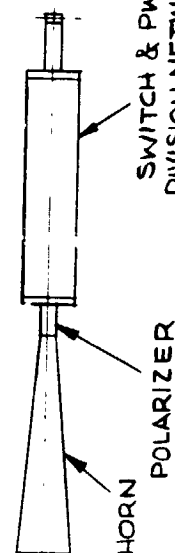
59 +

VOLUME (FT³)

617

TOTAL SCORE

143



HORN ELEMENT ASSEMBLY

+ADDITIONAL POWER OF PHASE SHIFTERS IS IMPOSSIBLE TO ASSESS NOW

Configuration H1 - Electronically Adjustable Feed, Dual Reflector, Movable Paraboloid

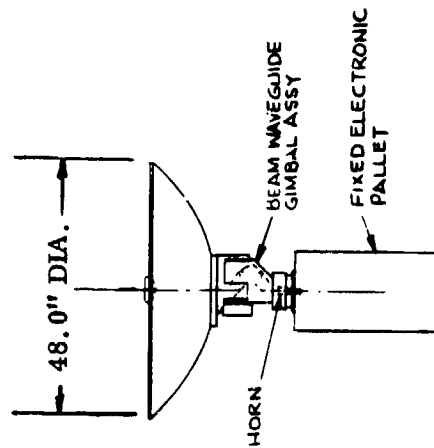
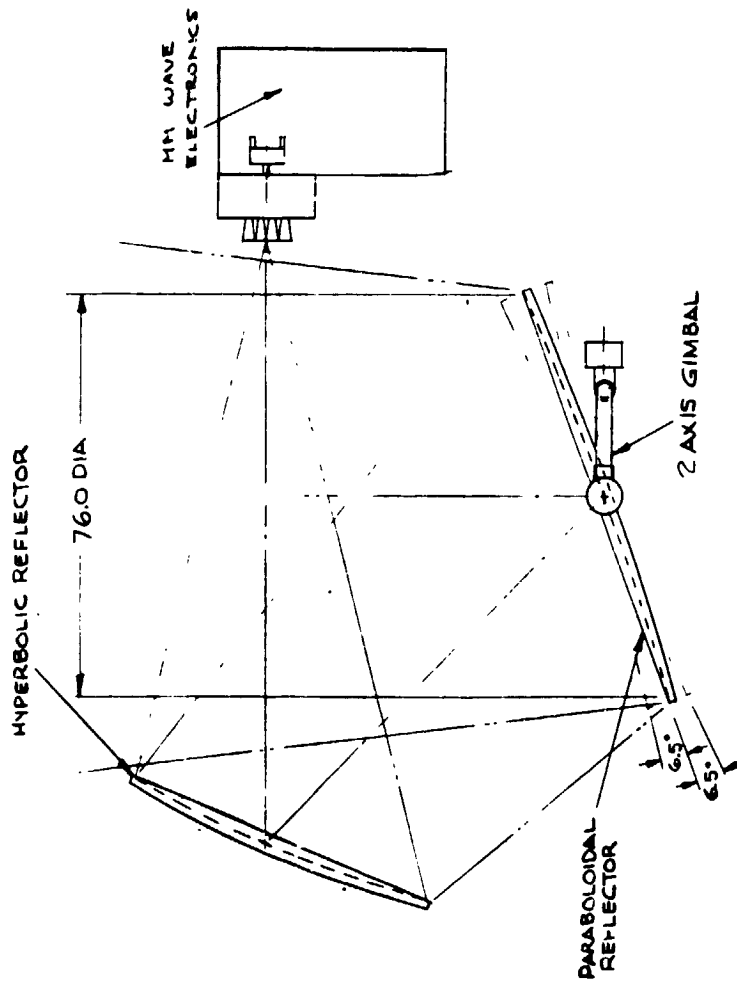
The large aperture size of this configuration is required to achieve the specified gain through a layer of phase shifters and two layers of variable power dividers, or more.

At least two levels of variable power dividers are required for a four feed array. This would be the minimum feed array that would allow for fine beam pointing by electronic means. An insertion loss of 2 dB for the divider tree must be provided for by an increase in aperture diameter of 26%.

If it is desired to compensate for beam distortion due to scanning, at least a seven element ring array feed should be employed. This will require three levels of variable power dividers and in addition a variable phase shifter behind each horn is needed. This adds up to 4 dB of insertion loss, or an aperture diameter increase of 58%, from 48" to 76". As in the case of the MBA antennas, 60 GHz reciprocal variable power dividers are required for this approach and they have not yet been demonstrated.



SIZE COMPARISON



B1 BEAM WAVEGUIDE FEED, CASSEGRAIN

H1 ELECTRONICALLY ADJUSTABLE FEED,
DUAL REFLECTOR, MOVABLE PARABOLOID

Configuration H1 - Electronically Adjustable Feed, Dual Reflector, Movable Paraboloid

In this approach the beam deterioration and sidelobe increase with beam scan of the M3 configuration can be substantially compensated for by use of a multiple feed array in which the phase and amplitude distribution is varied with the scan angle. This requires a reciprocal phase shifter behind each feed and at least two levels (for a four feed array) of reciprocal variable power dividers which are new component developments. The losses in this beam forming network must be compensated for by an increase in aperture size over the M3 size.



**GENERAL
ELECTRIC**

H1

**ELECTRONICALLY ADJUSTABLE FEED, DUAL REFLECTOR,
MOVABLE PARABOLOID**



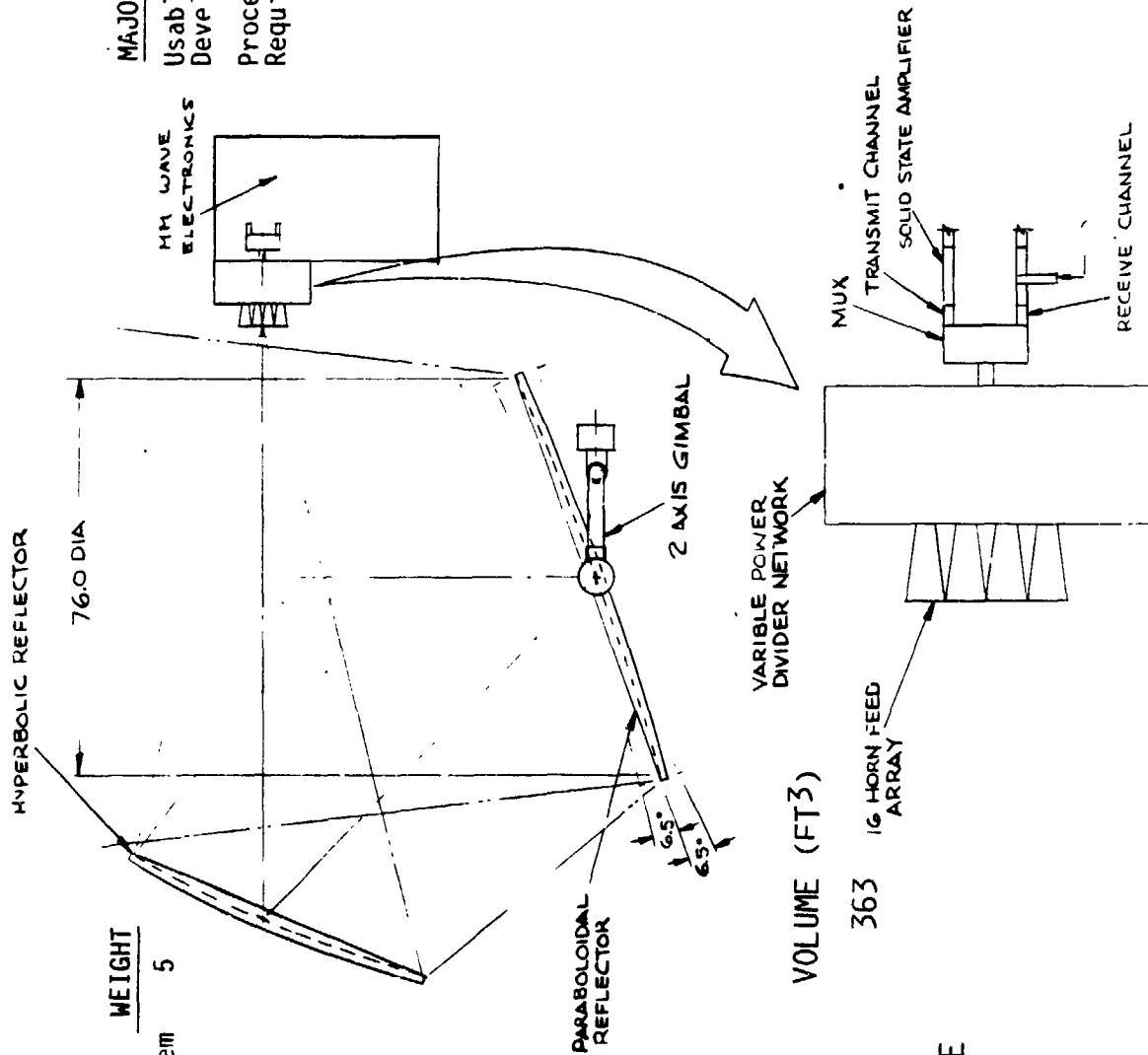
MAJOR STRENGTHS
Integration & System
Test Impact

WEIGHT
5

MAJOR WEAKNESSES

Usable TDAS Only
Development Risk 9

Processor
Requirements 3



WEIGHT (LBS) 167 **POWER (W)** 64 **VOLUME (FT³)** 363

167

64

363

TOTAL SCORE
201

Baseline Types - Reflector/Fixed Feed - Summary

Here the reflector/fixed feed configurations are reviewed in summary. Configuration B1, shown with various possible reflector geometries depending on spacecraft constraints, is the preferred system for both TDAS and user, i.e., small and large field of view. It scores highest in all electrical and mechanical parameters and also with respect to host spacecraft impact and integration and test. Configuration B2 scores equally high in all electrical parameters but falls off in the mechanical area in weight, power and volume. Its biggest drawback lies in environmental control and spacecraft integration and test. Neither of the two configurations shows any major disadvantages (score of 1). Configurations B3 and B4, with flexible waveguide and rotary joints respectively, are penalized by excessive RF loss and show poorly in reliability and development risk.



GENERAL
ELECTRIC

BASELINE TYPES - REFLECTOR/FIXED FEED - SUMMARY



		SCORE		USERS
		TDAS		
			B1	
			CASSEGRAIN REFLECTOR WITH BEAM WAVEGUIDE	
			395	
			B2	
			CASSEGRAIN REFLECTOR WITH ANTENNA MOUNTED ELECTRONIC PALLET	
			298	
			B3	
			CASSEGRAIN REFLECTOR WITH FIXED ELECTRONICS FLEXIBLE WAVEGUIDES (RDAS ONLY)	
			279	
DIAMETER			B4	240
			WITH ROTARY JOINTS	
			(TDAS AND USERS)	
			53"	69"

4. PROPOSED FUTURE ACTIVITIES

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PROPOSED FUTURE ACTIVITIES

The results of the Phase A tradeoff analysis were presented to NASA-GSFC on 23 February 1984. A written draft of the Phase A Report was released on March 16, 1984, and this Phase A final report contains additional information in response to NASA-GSFC comments and questions.

Phase B consists of two major task areas, the conceptual design of the preferred antenna system(s) to be selected by NASA-GSFC and the assessment of the development status for critical technology items.

The summary report at the conclusion of the study will cover both Phase A and B results.



60 GHz ANTENNA SYSTEMS ANALYSES
FOR INTER-SATELLITE LINKS



PROPOSED FUTURE ACTIVITIES

- PHASE A
 - PRESENTATION AT GSFC
 - DRAFT/FINAL REPORT
- PHASE B
 - SELECTION OF PREFERRED ANTENNA SYSTEM(S)
 - CONCEPTUAL DESIGN
 - o EL/ME CONFIGURATION
 - o POINTING AND AUTO TRACK
 - o CONTROL ELECTRONICS
 - o HOST S/C IMPACT
 - o PERFORMANCE SUMMARIES
 - TECHNOLOGY DEVELOPMENT STATUS
 - o MONOPULSE FRONT END
 - o FLEXIBLE WAVEGUIDE
 - o LOW LOSS ROTARY JOINT
 - DRAFT/FINAL SUMMARY REPORT

APPENDICES

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APPENDIX A

ELECTRONIC SCAN ANTENNA SYSTEMS

I. THE MBA

The first consideration for an MBA design is the choice between a square and a triangular matrix of beams to blanket the coverage solid angle. For the case where only a single resultant beam is required, where the coverage solid angle is circular, and where no adaptive nulling is required, the triangular matrix is the superior choice, as the gain at the three beam intersection is higher than that at the four beam intersection for the square matrix. The number of singlet beams required to cover the solid angle that is 26° across is a function of the level at which adjacent singlet beams cross each other. A great amount of past effort has been devoted to optimizing this cross-over level. If an attempt is made to cross the beams at too high a level, the aperture spillover of the feeds, and high feed mutual coupling will reduce the singlet gain and the number of beams (and feeds) per unit solid angle will increase. If the cross-over is chosen at too low a level, the composite beams formed by the summing of adjacent beams when the coverage beam is between singlets will be substantially reduced in gain with respect to the singlet beam peaks.

The optimum adjacent beam cross-over level was found to be at approximately the -5.3 dB level with respect to the singlet beam peaks (this level is used on DSCS III MBSs). For this cross-over level the center point of a three beam intersection falls 7.1 dB below a singlet peak. The sum of the three intersecting singlets is then -2.3 dB with respect to the peak gain of a single adjacent beam. The aperture must be designed to accommodate this as 2.3 dB of additional peak gain. Two other factors must be considered in sizing the aperture. There will be a scan loss due to the necessity of placing some of the feed horns relatively far from the aperture focal point (the furthest singlet will be more than 85 half

power beamwidths from the central beam). The amount of scan loss will be a function of the optics design of the aperture. A Luneberg lens would entail no scan loss but would be prohibitively heavy. A very optimistic estimate of 1 dB of scan loss will be used to illustrate that even the best possible MBA design will not be cost effective. For this reason tolerance effects will not be considered. One loss that must be considered is due to the beam forming network (configured as in Figure 1). Two levels of variable power dividers (VPDs) are required with an insertion loss of 1 dB per level, and at least 12 levels of solid state switches are needed with an insertion loss of 0.2 dB per level. Thus a loss in the beam forming network of at least 4.4 dB must be assumed. The aperture must generate a singlet peak gain of $54 + 2.3 + 1 + 4.4 = 61.7$ dB. This will require an 8 foot aperture for the spill-over levels consistent with -5.3 dB adjacent beam cross-overs. Each singlet beam will thus have a half power beamwidth of 0.15° as deduced from the aperture diameter.

Figure 2 shows a portion of the coverage solid angle of 531° ² that results from the 13° half cone angle requirement for the TDAS spacecraft. It can be seen that each beam must cover a hexagonal solid angle, the area of which is 12 times that of the small triangle marked "a" in the figure. The small triangle is a right triangle with one side equal to half the adjacent beam cross-over width and an acute angle of 30° . The adjacent beam cross-over width can be calculated from the HPBW by assuming a Gaussian beam (this is an accurate assumption near the beam peak). The HPBW of 0.15° leads to a hexagon of $.0345^\circ$ ². It would take approximately 15,391 such hexagons to fill the required solid angle (and therefore 15,391 feed horns to form as many singlet beams). Each horn is assigned as a number one, two, or three in accordance with the pattern shown in the figure such that no beam is adjacent to one generated by a horn of the same number. Each of the 5130 horns of a common number is connected by a 13 level (some horns

utilize 12 levels) binary switch tree to a common port. The three common ports are then connected by two levels of variable power dividers to a common single port as indicated in the figure.

It can be seen that any point in the coverage region is either on a beam peak, on a line between two beam peaks or is in the area between three beam peaks. Three adjacent singlets are always a one, a two, and a three beam set which can be selected by the proper setting of the binary switch tree to be fed into the variable power divider tree. The variable power dividers can be set to provide a gain maximum at the desired point.

Each hexagonal portion of the coverage region is provided by a feedhorn, therefore if it is desired to generate more than one beam from an MBA antenna that can be aimed to every point in the coverage region, a means of sharing the horns must be devised. Two simultaneous beams can be generated by employing two orthogonal polarizations (i.e. right and left hand circular). To accomplish this an orthomode transducer must be employed with each feed horn with each of its two outputs feeding into a 13 level switch tree followed by a two level variable power divider tree. An N beam antenna can be provided if each beam operates in a different frequency band and an N way frequency multiplexer is connected behind each feed horn followed by N switching and variable power divider trees.

It should be noted that 60 GHz ferrite circulator switches with .2 dB loss are state-of-the-art, but the reciprocal variable power dividers in this band with 1.0 dB of loss do not yet exist.

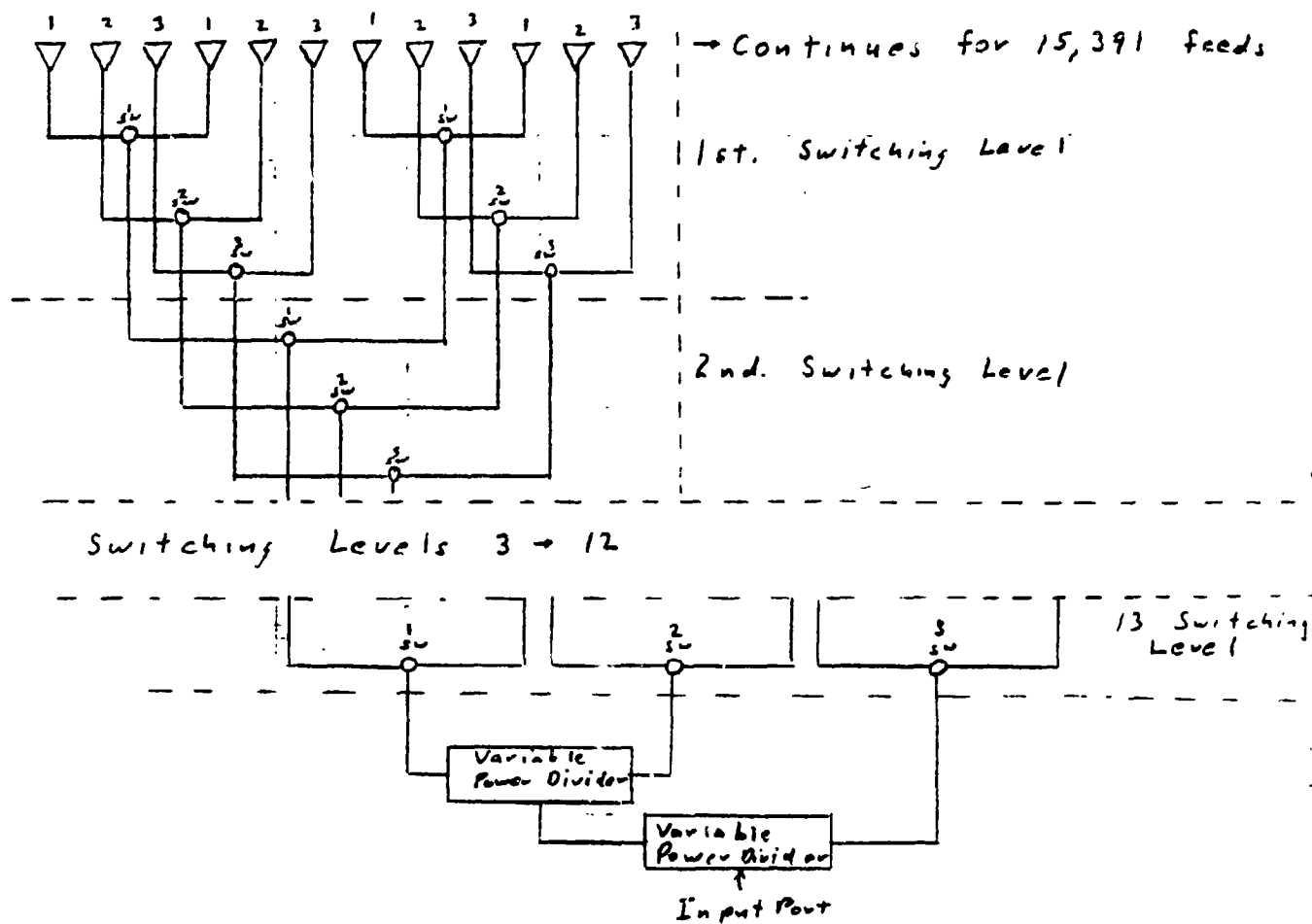


FIGURE 1. - MULTIBEAM ANTENNA BEAM FORMING NETWORK

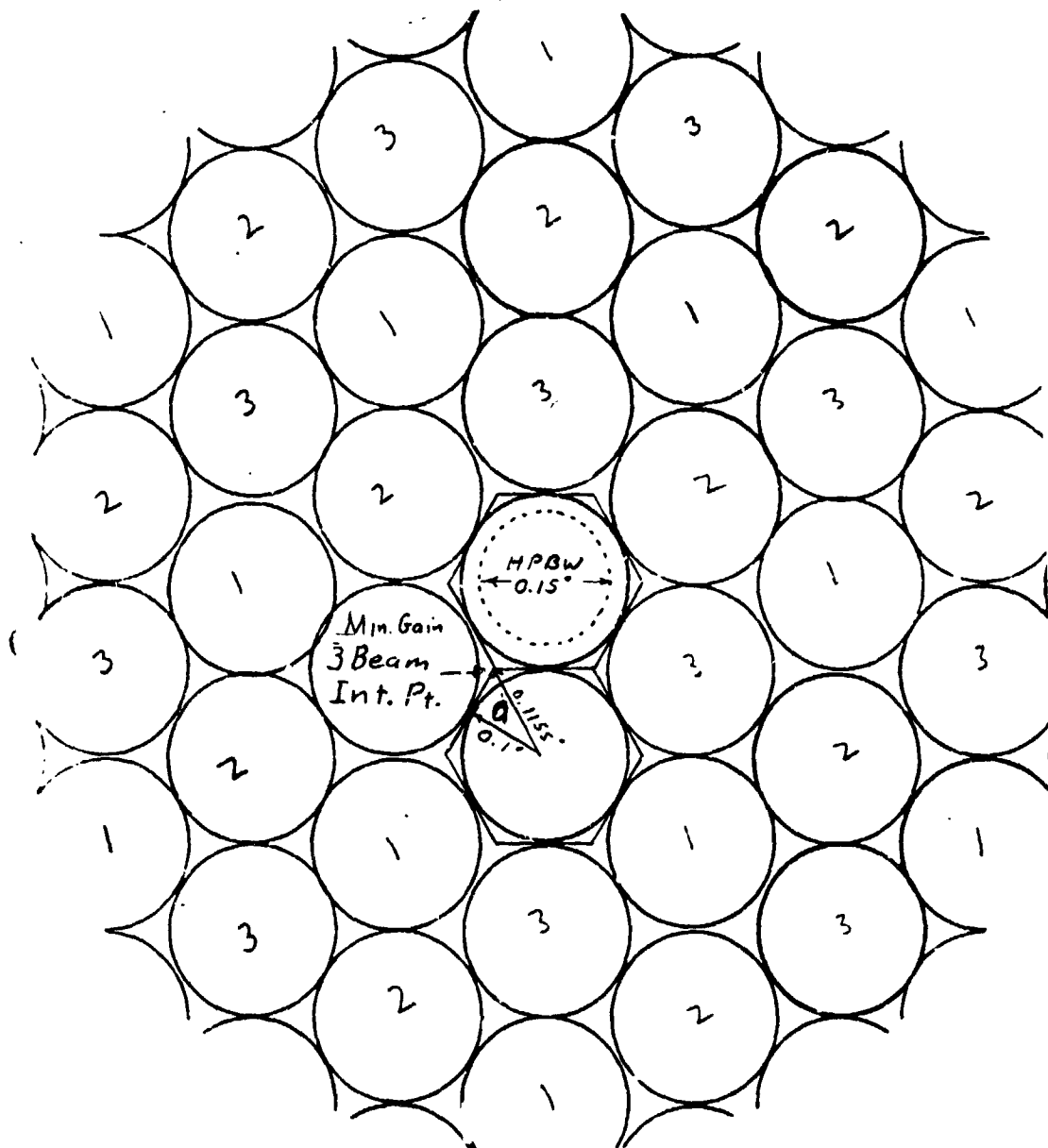


FIGURE 2. - TRIANGULAR BEAM MATRIX

II. THE PHASED ARRAY

To size the phased array design it will be assumed that it is necessary to avoid echelon lobes appearing in the coverage solid angle. To make use of all the available aperture, an array of square horns in a square matrix will be evaluated. To avoid spurious lobes the maximum horn spacing is given by:

$$S \leq \frac{\lambda}{2 \sin \theta}$$

where λ is the wavelength and θ is the maximum scan angle. For $S = .425"$ the echelon lobe does not appear between -13° and $+13^\circ$ when the beam is in its maximum scan position. Figure 3 is a computed pattern of a 900 element portion of the array. The peak edge of coverage gain of this array is seen to be 43.57 dB. Thus 10,000 elements would have a worst case scan gain of 54.03 dB if there were no losses in the feeds and polarizers, and if no redundancy is required. Estimating losses at 0.3 dB and allowing for 5% redundancy requires an array of 11,236 (106×106) elements. Each element is a square pyramidal horn .14" x .14" x 1." with a half power beamwidth of 27.5° and a peak gain of 16.68 dB. The pattern computation of Figure 3 was made for a 5 bit phase shifter per horn with ± 0.5 bit of random phase error. These phase shifters are available at this frequency with about 1. dB of insertion loss but they are of a non-reciprocal ferrite design. Thus the same phase shifter could not be used for both transmit and receive. Diode phase shifters that are reciprocal would have at least 3 dB of insertion loss at 60 GHz. Figure 4 is a block diagram of one element of a design that would share the feed array and phase shifter between the transmit and receive functions. The insertion loss of the phase shifter, circulator, and the increased filter losses in the transmit and receive filters necessary to achieve sufficient isolation between the transmit and receive units is about 3.7 dB. Thus the array size would have to grow to 26,340 horns to obtain the same performance that 11,235 horns each can achieve in separate transmit and receive arrays.

The same methods of achieving multiple beam operation suggested for the MBA antenna can be used in the phased array, however. the multiple waveguides coming off each horn would generate a complex mechanical interface. In addition, everything except the horns would have to be duplicated for each beam, and if more than two beams are required, an N way frequency multiplexer must be included behind each of the more than 26,340 horns (more because the array would have to be increased in size to allow for the insertion loss of the multiplexers).

Multiple beams can be generated from a phased array if each element can be controlled in both phase and amplitude, however, the array gain would then have to be shared between the beams, and the number of elements would have to increase by more than a factor of N for N beams and nothing is gained.

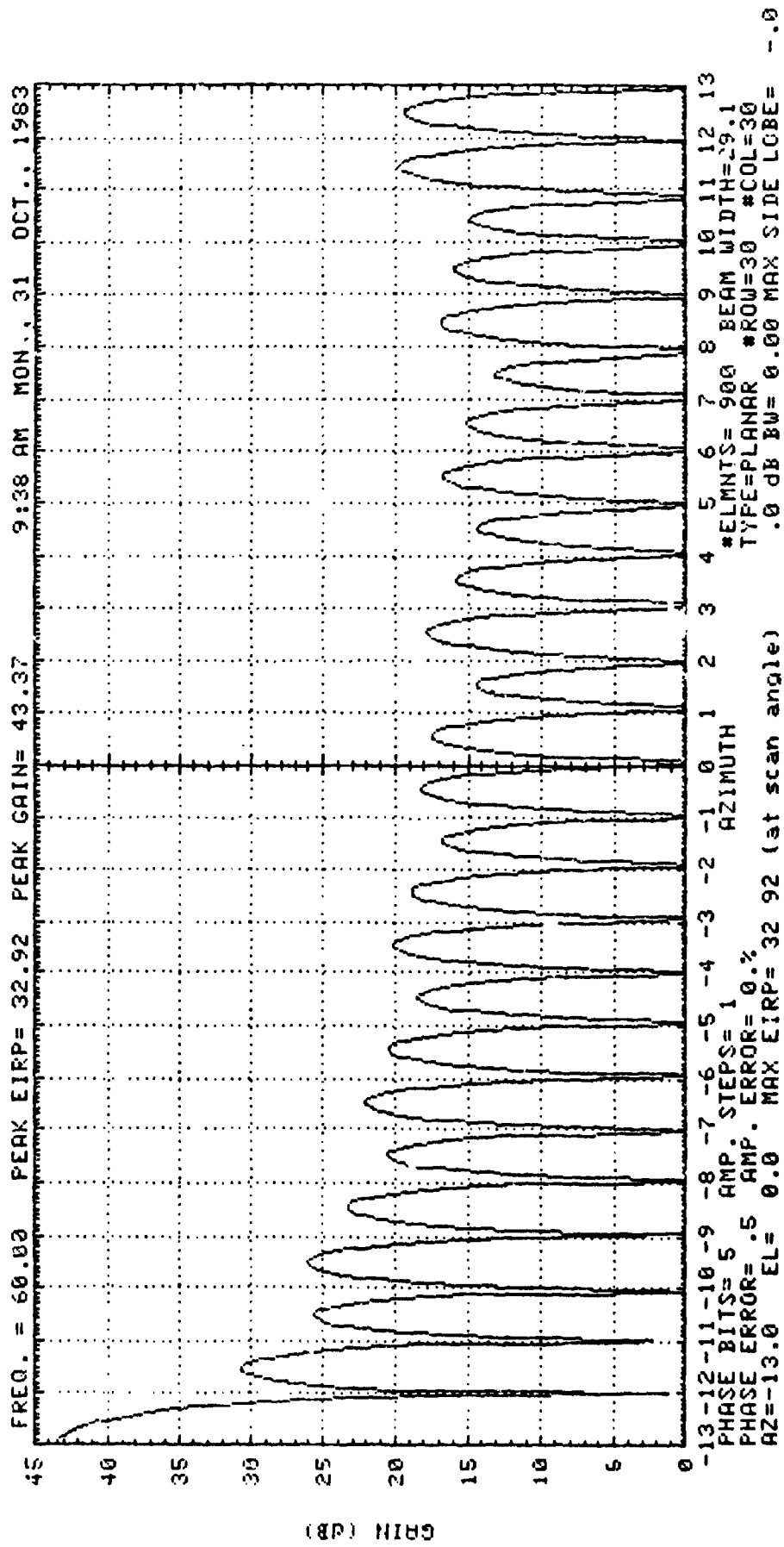


FIGURE 3. MAXIMUM SCAN PATTERN OF PARTIAL ARRAY

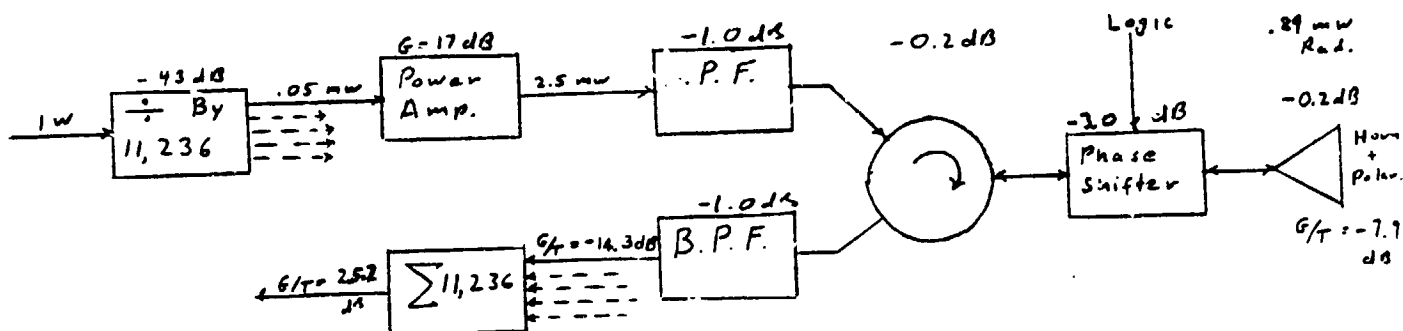


FIGURE 4. - BLOCK DIAGRAM FOR SHARED TRANSMIT/RECEIVE ARRAY ELEMENT

APPENDIX

BEAM WAVEGUIDE ANTENNA FEED

General Electric Space Systems Division began work on the millimeter-wave beam waveguide antennas in early 1982 as the result of extensive design trade-offs on millimeter-wave crosslink antenna configurations. The trade-offs were directed at finding a low weight, compact and reliable solution to the problem of providing a gimbaled millimeter wave antenna with a low loss path between the moving feed and critical receiver and transmitter components.

Figure 1 shows the configuration of the beam waveguide approach. The design produces a virtual image of the feed in the moving reflector assembly. The beam waveguide path can be divided functionally into two parts. The two offset paraboloids refocus the beam and provide an identical image of the feed horn at a suitable distance from the actual feed. The refocusing also constrains the beam diameter so that it can be contained inside an enclosure. The back-to-back arrangement allows the two paraboloids to cancel the slight distortions introduced by the off set geometry. The two flat mirrors then provide two opportunities for an axis of rotation without distortion or loss. The system, being a guided wave structure has low loss, with the two loss mechanisms being spillover and resistive losses on the reflectors. If the mirrors and paraboloids are large enough and have a good finish, these effects are very small. The concept is not new and has been in use in ground stations in the United States, Japan and Germany for over 9 years. GTE Sylvania, for instance, has used the system in 19 different installations. Table 1 lists some of the more important references to the technique in the literature.

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General Electric Space System Division has developed multiple, analytical computational tools to accurately compute the r.f. pattern produced by this feed arrangement. New computational tools were required because the paraboloids operate in the near field of the horn and each other.

The primary GE analytical tool for the near field solutions is called SMEPT or Spherical Mode Expansion and Reconstruction Technique. In this technique the far field pattern is calculated in terms of spherical modes and then the near field is reconstructed by a far field to near field transformation. This technique has been validated by comparing its results to rigorous physical optics computations. The SMERT technique is very effective, since it takes 5 to 10 times less computer time than near field physical optics computations. The SMERT program was used to compute the performance of the beam waveguide path over a range of mirror diameter, spacings and frequencies. Figure 2 shows the definition of terms used in the data. The two flat mirrors have been eliminated from the analysis since, if they are sufficiently large, they produce a perfect image. Figure 3 demonstrates the large bandwidth capability of the beam waveguide system. The term efficiency indicates the percentage of power output over the power input ($0.25\text{dB} = 94.4\%$). Figure 4 shows the effect of paraboloid separation at 60GHz , indicating that a wide variety of geometries can be handled. Long paths require slightly larger mirrors for the same loss.

From Figure 3 it is apparent that the mounting distance between paraboloids is not critical. The angular alignment of the flat mirrors also does not affect efficiency but only presents a bias offset in beam direction. The other alignments are more critical; however, analysis has shown that compared to the open loop pointing accuracy of 0.05° for the gimbal mechanism they are not as critical as the bearing and encoder alignments, which are required for any of

the mechanically scanned alternative configurations.

Experimental confirmation of the analysis results were obtained with the bench test configuration shown in Figure 5. First, a multimode horn was constructed and tested at 60 GHz. The results of its test and the comparison with its calculated patterns are shown in Figure 6. Second, the horn was mounted on the beam waveguide bench test set up per Figure 5 and the output pattern was measured. This pattern is shown in Figure 7, and over the angle of cassegrain sub-reflector illumination the pattern is identical to the horn alone. The differences between the patterns at wider angles is due to the fact that the parabolic mirrors were not constructed to the proper offset distance. However, these differences exist in the area where the energy spills over the cassegrain sub-reflector. These errors serve to illustrate the insensitivity to dimensional tolerances. Figures 8 and 9 show the calculated sum and difference pattern at the output of a beam-waveguide cassegrain system. The only perturbation caused by the beam waveguide is a slight bore sight shift in one plane. This represents a stocic bias error of a small fraction at a beamwidth and would not affect system performance.

The technique is very attractive, as shown by the trade-off conducted in this study, however, its implementation on a spacecraft program will require a prior demonstration of the performance of the entire beam waveguide mechanism with a large Cassegrain reflector.

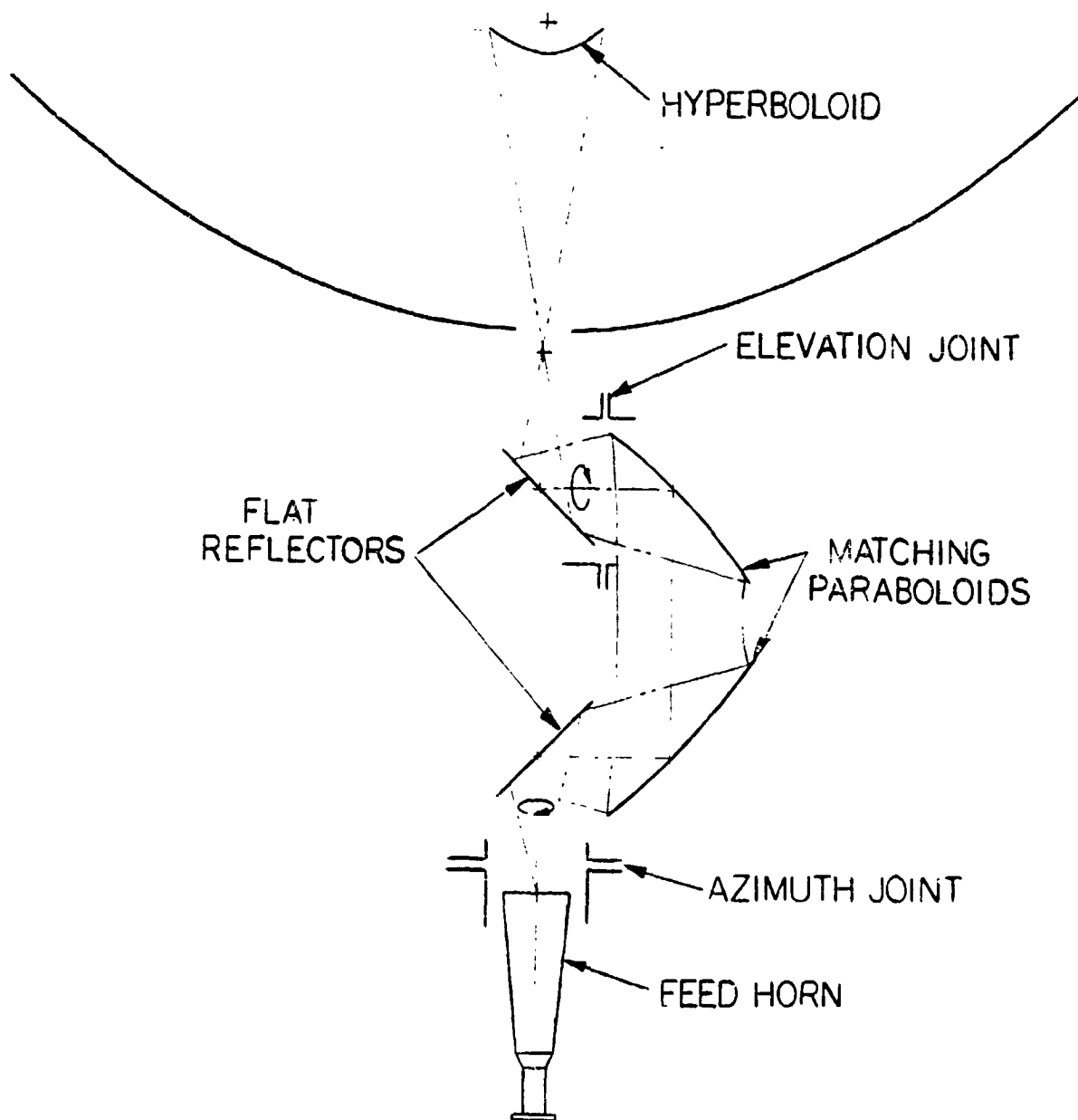


FIGURE 1 - BEAM WAVEGUIDE CONFIGURATION

- PROVEN GROUND ANTENNA TECHNIQUE

BELL LABS 1964

FIRST ANALYSIS AND EXPERIMENTAL DATA

THE REFLECTING BEAM WAVEGUIDE,
IEEE, MT&T JULY 1964 P. 445-453

DEGENFORD, SINKIS & STEIER,

TRG 1966

EXPERIMENTAL CONFIRMATION

MILLIMETER WAVE ANTENNAS, ALLEN KAY, PROC. IEEE, APRIL 1966
P. 641-647

AEROSPACE CORP. 1970

96 GHz OPERATIONAL SYSTEM

A FOCUSED APERTURE MILLIMETER WAVE TRANSMISSION LINE, C. YOWELL,
AEROSPACE REPORT TR-0059 (6230-30), NOV. 1970

mitsubishi 1973

THEORETICAL BASIS FOR DUAL PARABOLOIDS

A BEAM-WAVEGUIDE FEED HAVING A SYMMETRIC BEAM FOR CASSEGRAIN ANTENNAS,
MITSUBISHI & KITSUREGAWA, IEEE, A&P, NOV. 1973, P. 884-886

SYLVANIA 1975

ONE OF MANY OPERATIONAL GROUND STATIONS

BEAM WAVEGUIDE FEED WITH FREQUENCY-REUSE DIPLEXER FOR SATELLITE COMMUNICATIONS
EARTH STATIONS, SOMMERS, PARAD & DITULLIO, MICROWAVE JOURNAL, NOV. 1975, P 51-57

BELL LABS. 1975

ANALYTICAL & EXPERIMENTAL BWG FEED

SOME FAR-FIELD STUDIES OF AN OFFSET LAUNCHER, GANS & SEMPLAK, BELL SYSTEMS
TECHNICAL JOURNAL, SEPT. 1975, P. 1319-1340

BELL LABS. 1975

EXTENSION OF ANALYSIS & EXPERIMENTS

TABLE 1 - BEAM WAVEGUIDE REFERENCES

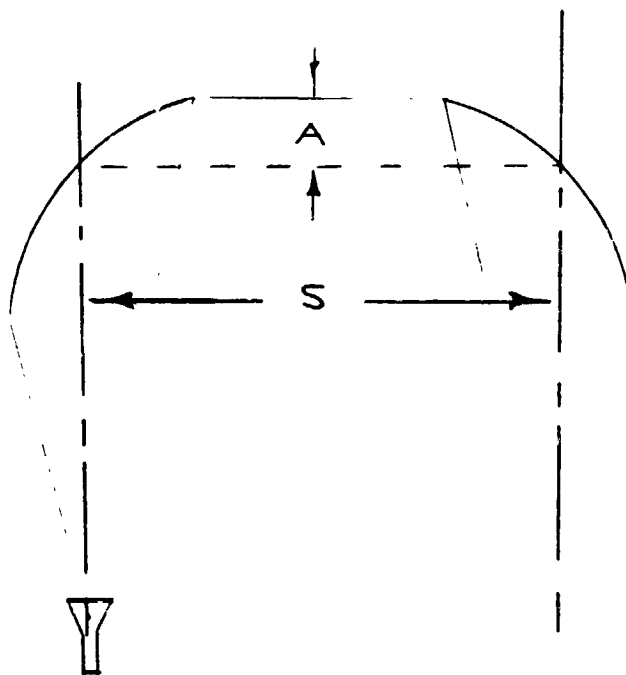


FIGURE 2 - DEFINITION OF TERMS

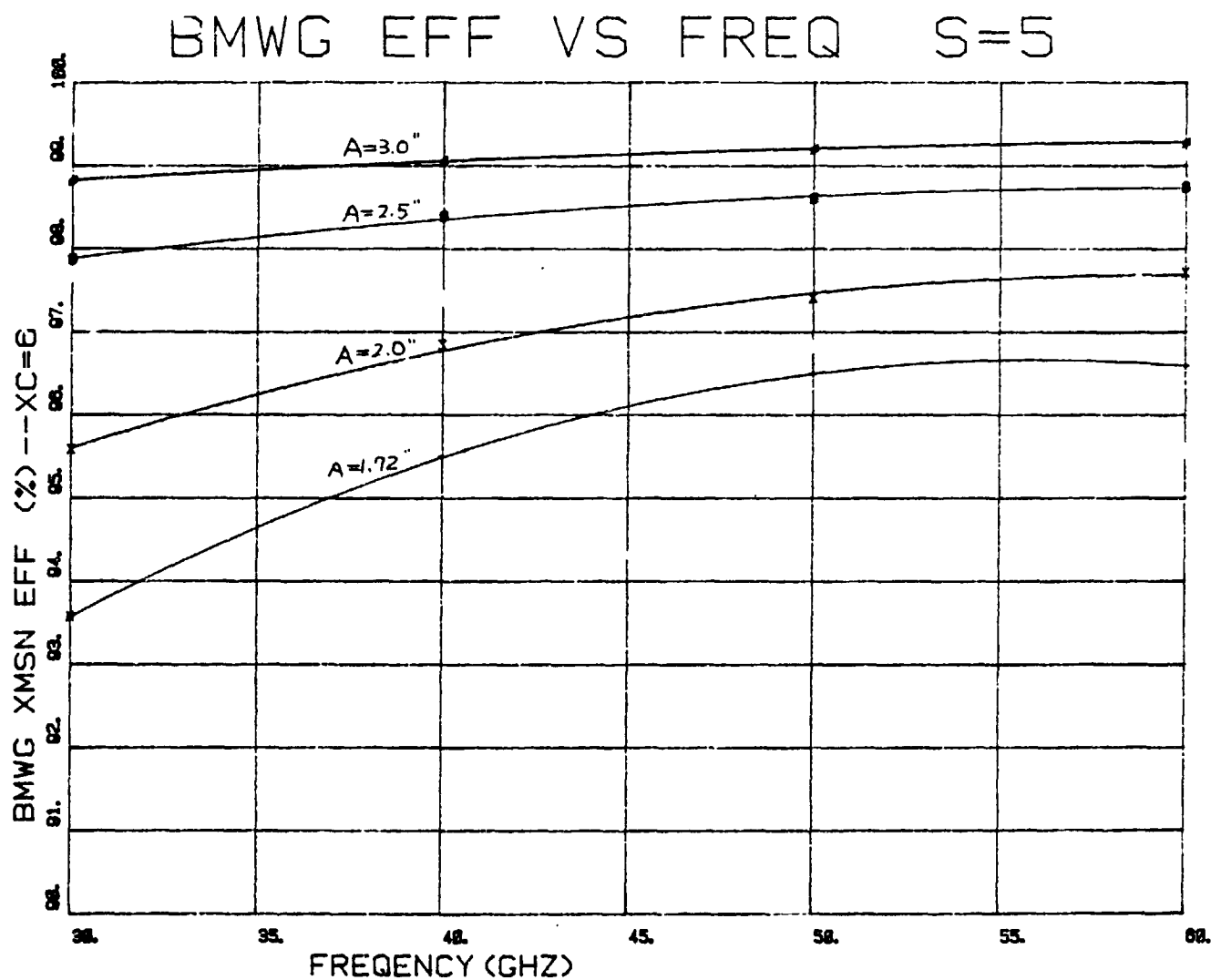


FIGURE 3
BEAM WAVEGUIDE TRANSMISSION EFFICIENCY
V.S. FREQUENCY

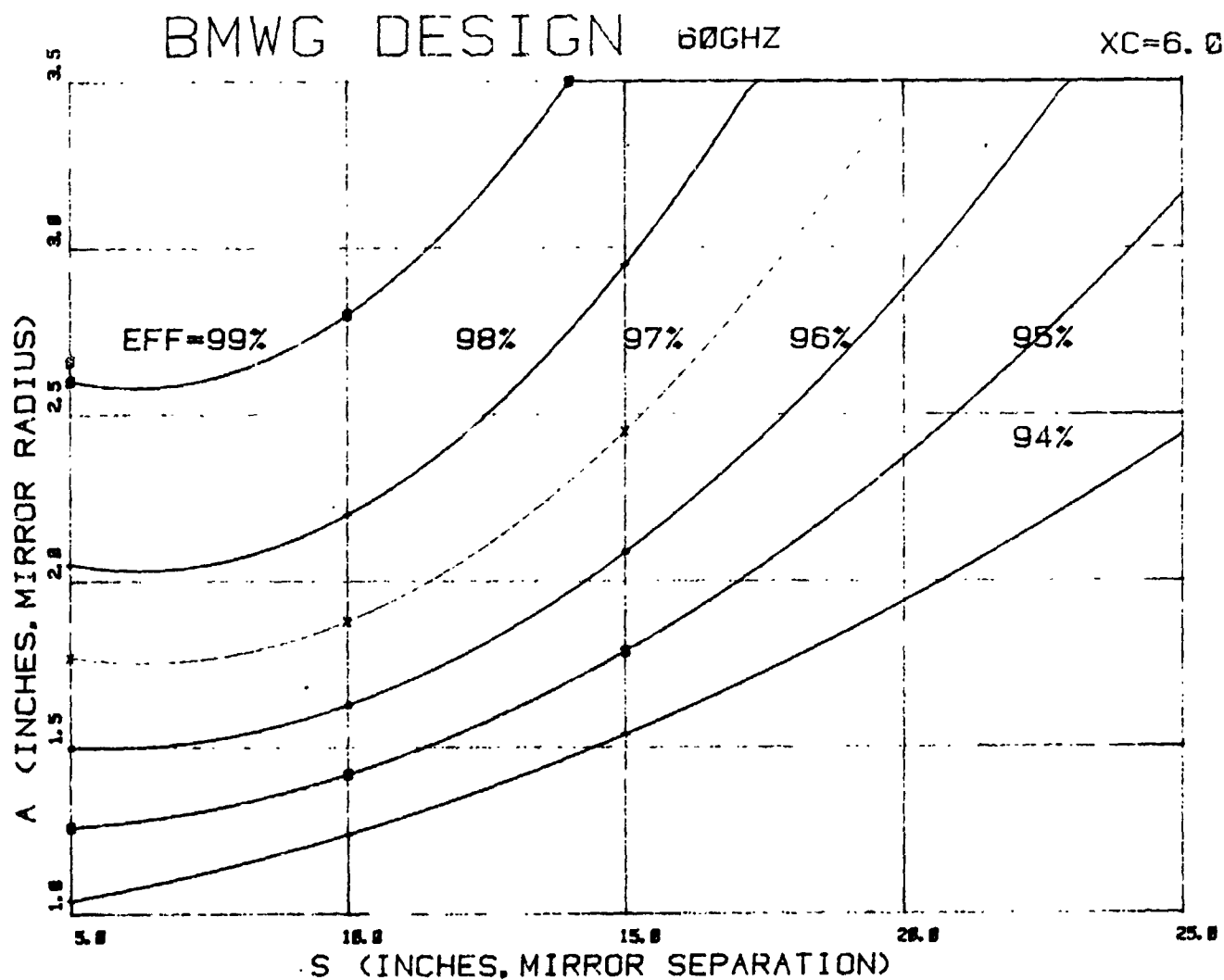


FIGURE 4
BEAM WAVEGUIDE TRANSMISSION EFFICIENCY
V.S. MIRROR SPACING
(60 GHZ)

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OF POOR QUALITY

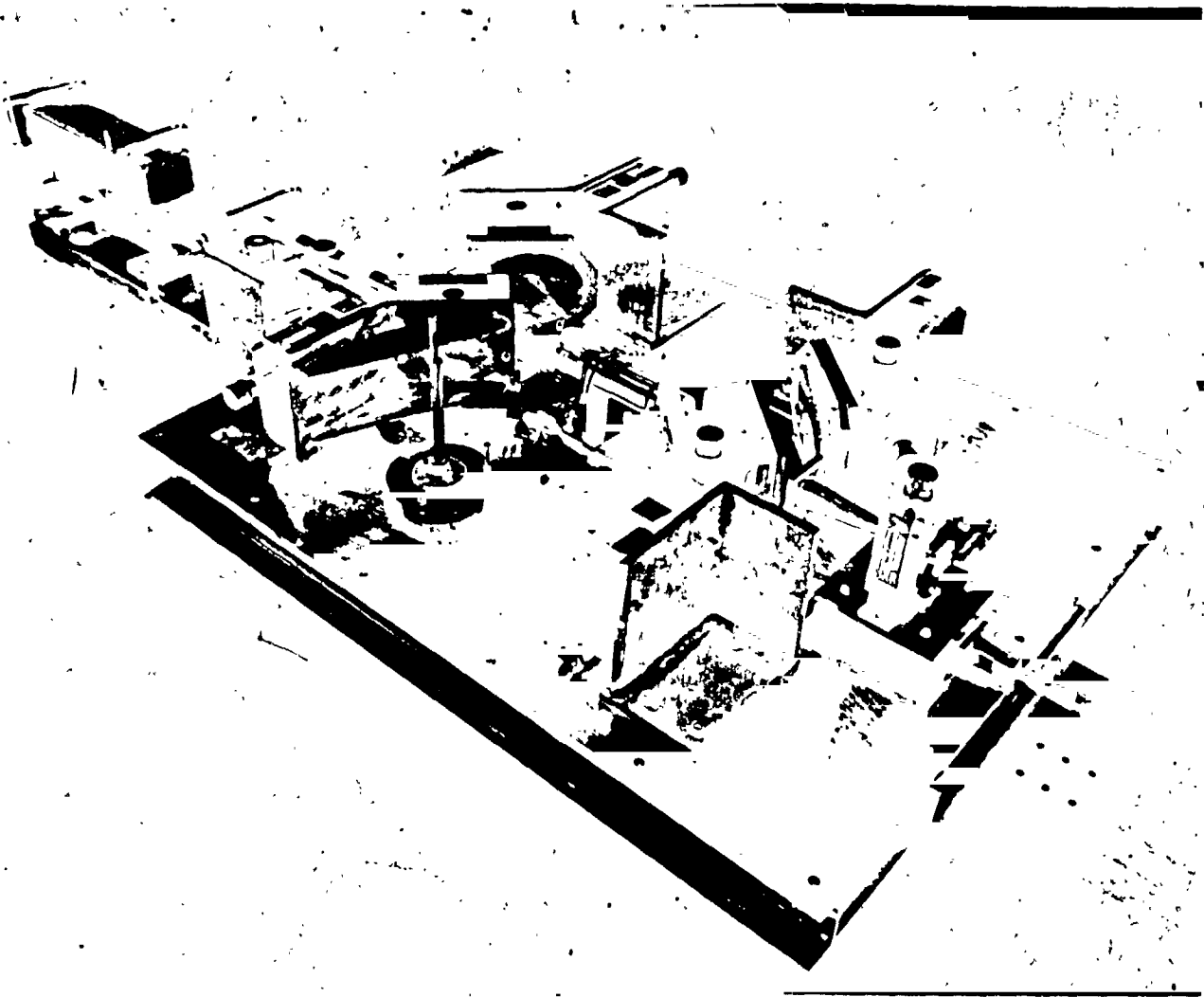


FIGURE 5 BEAM WAVE BENCH TEST SET UP

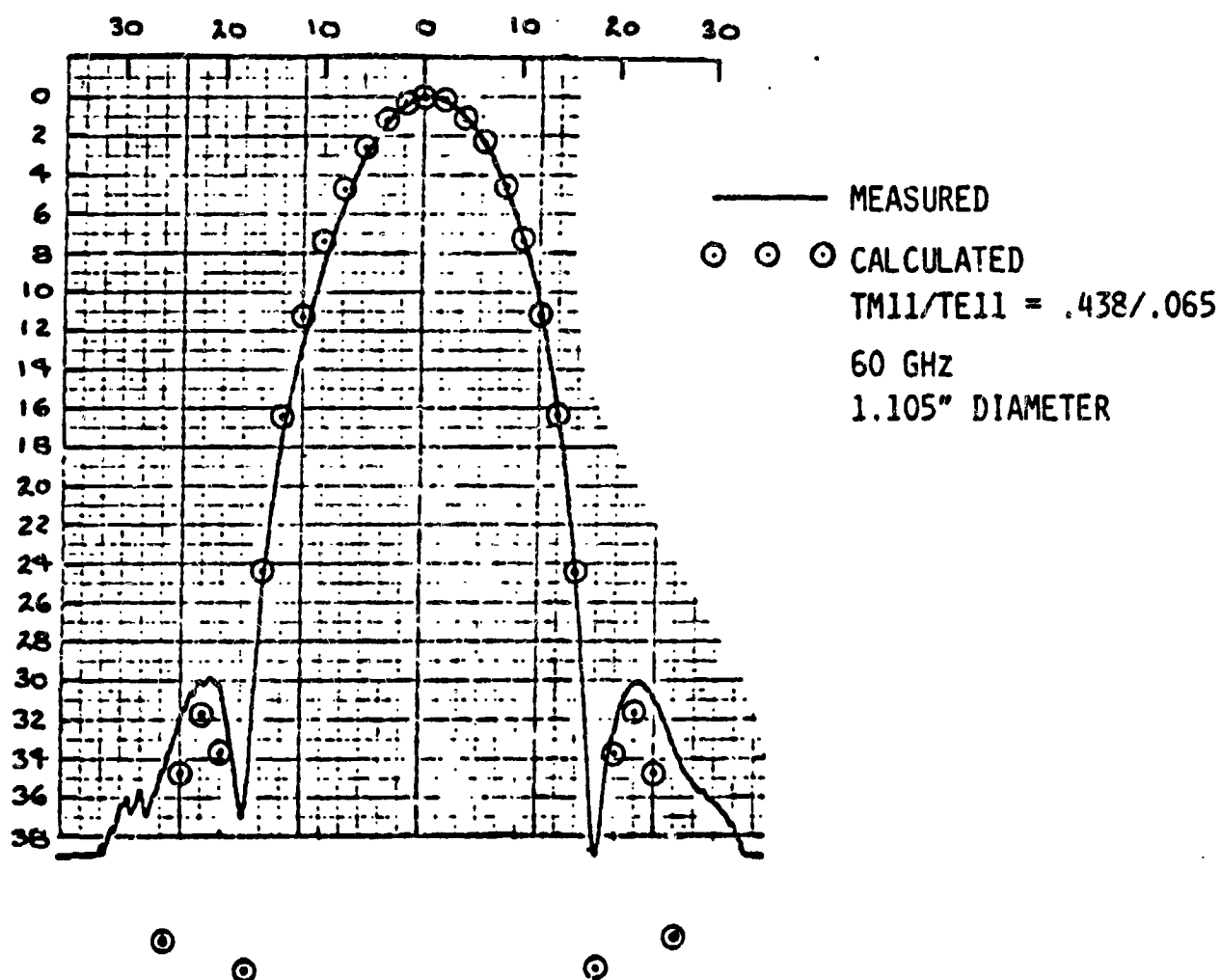


FIGURE 6
 MULTIMODE FEED PATTERN
 TM_{11}/TE_{11}
 MEASURED V.S. CALCULATED

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OF POOR QUALITY

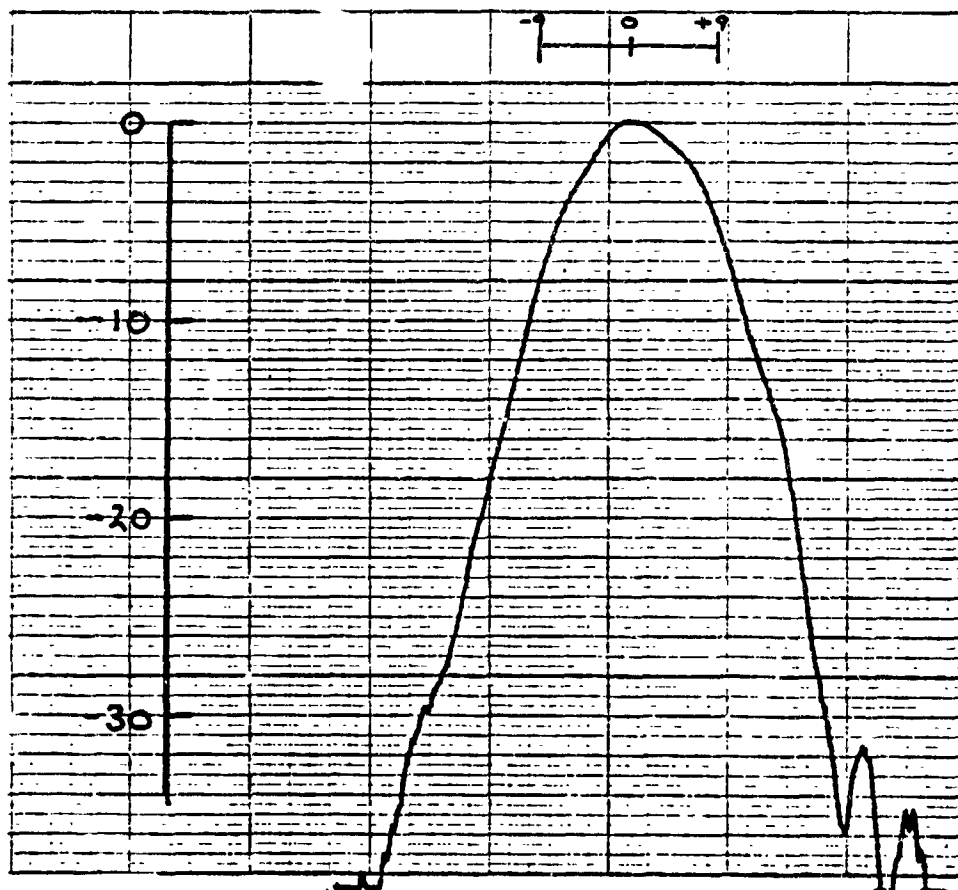


FIGURE 7
BEAM WAVEGUIDE OUTPUT

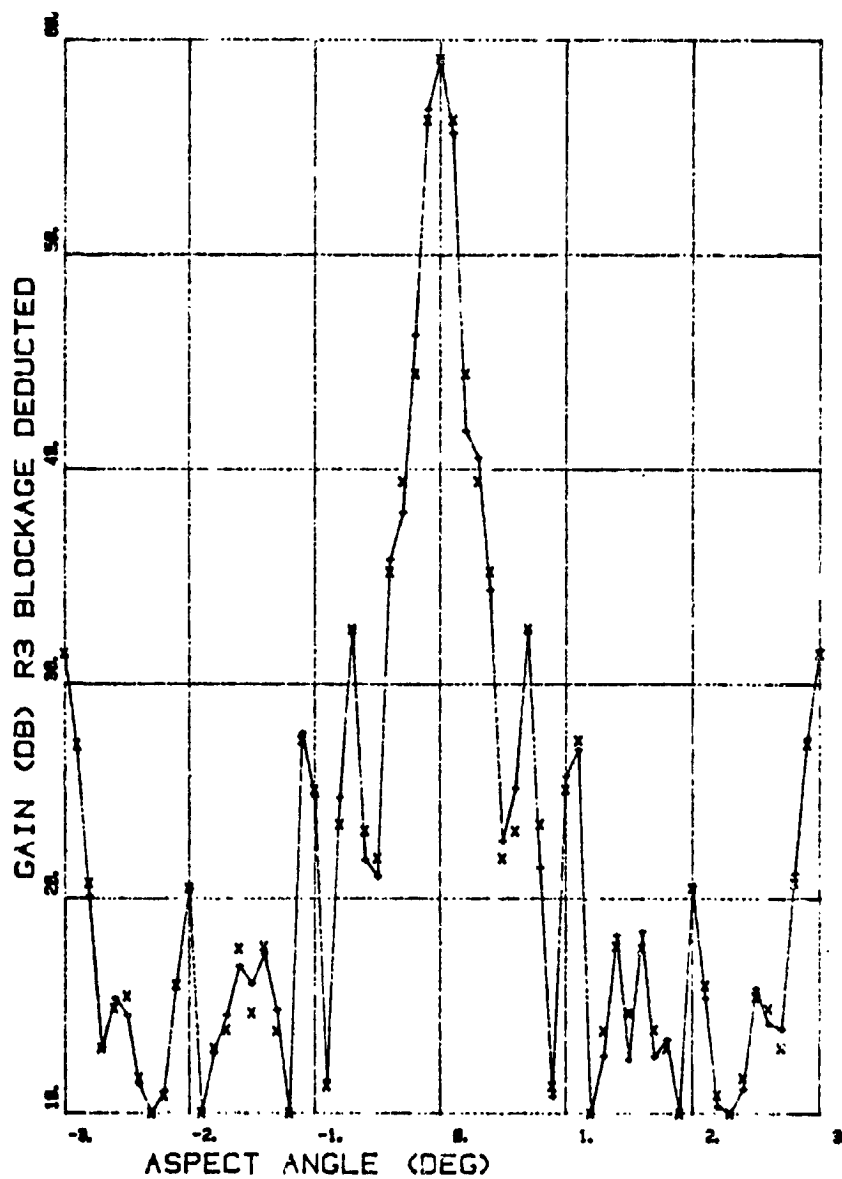


FIGURE 8

MAIN BEAM PATTERN
TOTAL BEAM WAVEGUIDE SYSTEM
(72" REFLECTOR)

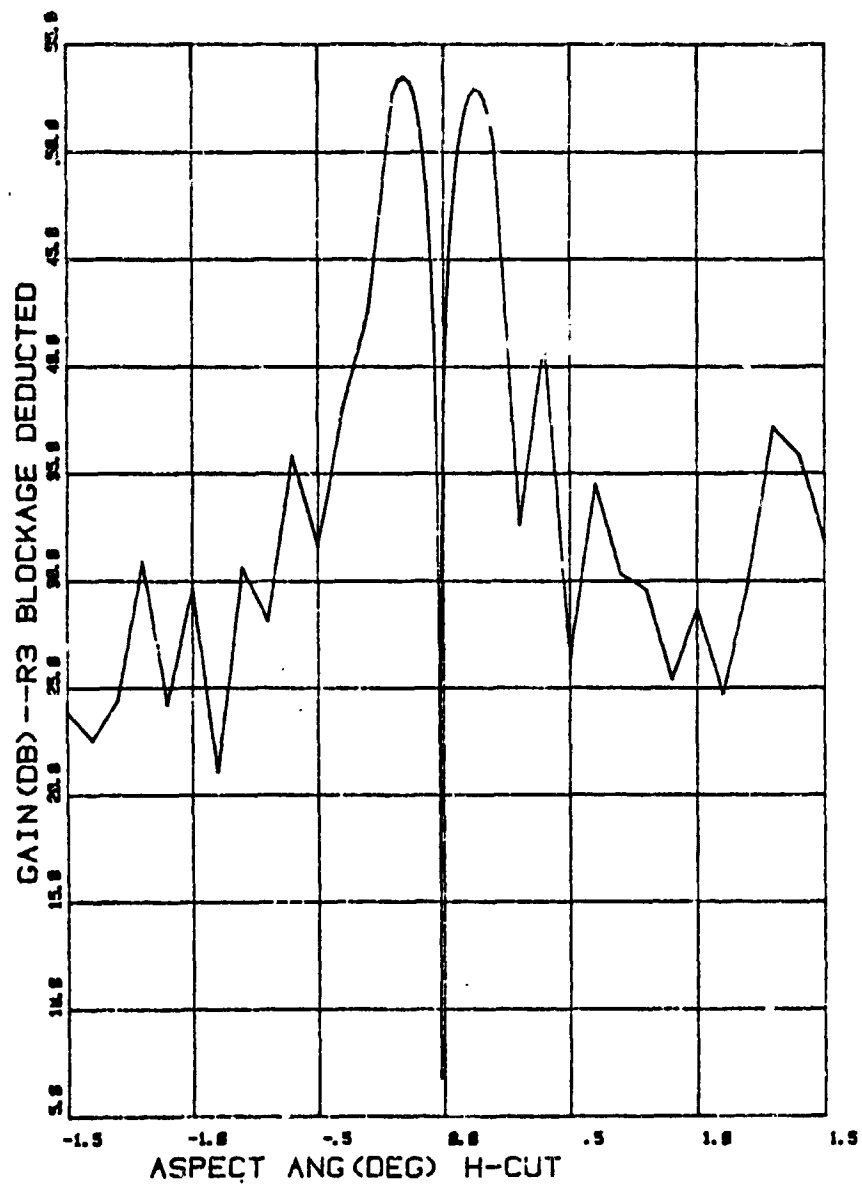


FIGURE 9

TE21 PATTERN

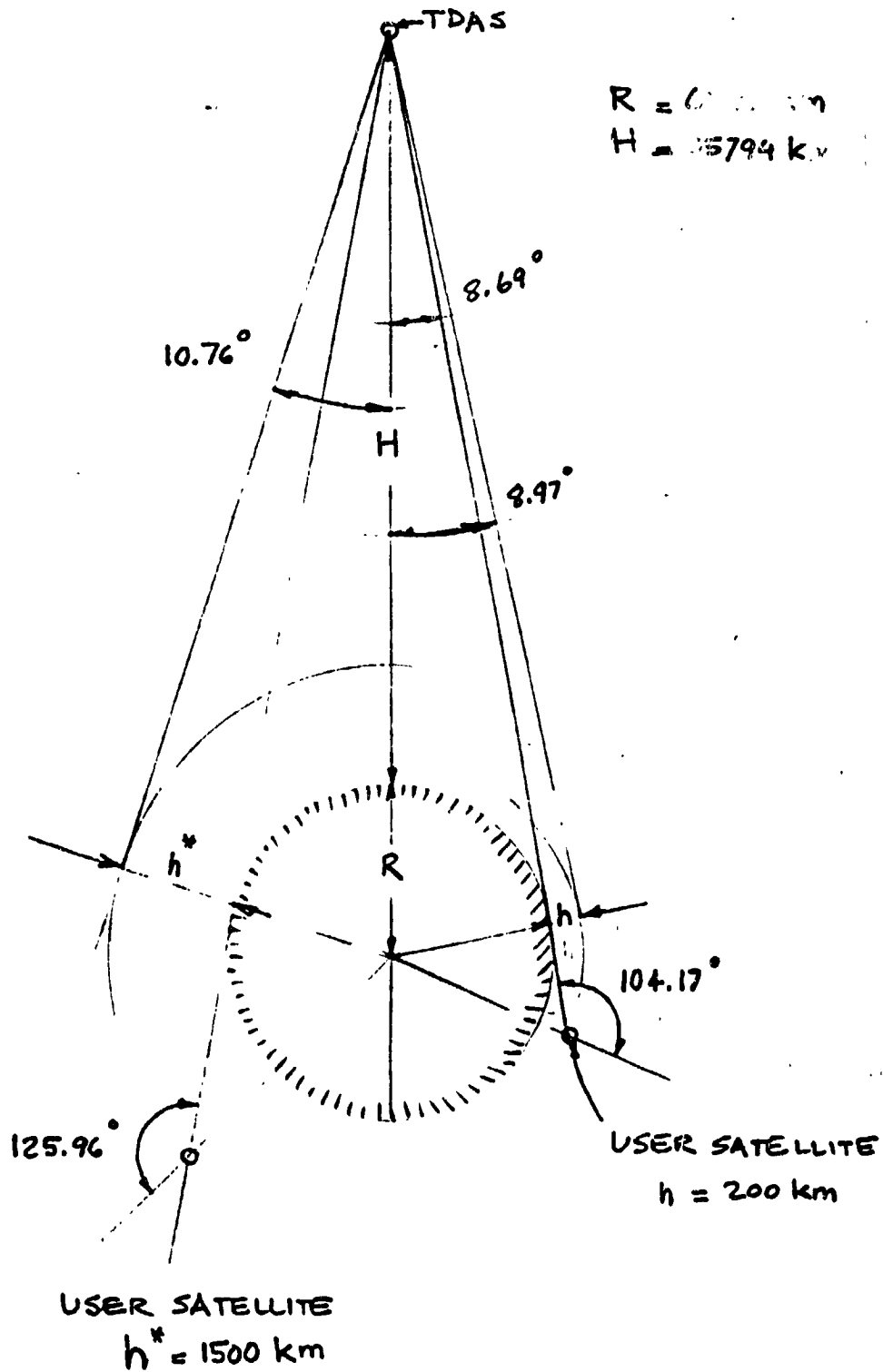
TOTAL BEAM WAVEGUIDE SYSTEM

(72" REFLECTOR)

APPENDIX C

FIELD OF VIEW REQUIREMENTS FOR TDAS AND USER SATELLITES

(Revised 12-9-83)



APPENDIX D

LINK BUDGET

Transmit Power	P_T (dBW)
Transmit Antenna Pk. Gain	54 dB
Pointing Loss	-0.1 dB
Free Space Loss	-221.3 dB ($36.6 + 20 \log f + 20 \log d$)
Receiver Antenna Gain	54.0 dB
Receiver Pointing Loss	-0.1 dB
Polarization Loss	-0.1 dB (2 dB Axial Ratio)
Noise Power Density	-198.1 dBW/Hz
Available P_r/N_0	$(84.5 + P_T)$ dBW/Hz
Data Rate 50 MBps	77 dB
E_b/N_0 @ 10^{-7} BER	4.8 (R1/2, K = 7 Viterbi Decoder)
Required P_r/N_0	81.8 dBW/Hz
Margin	3 dB
Required P_r/N_0 with Margin	84.8 dBW/Hz
Transmit Power Required - P_T	0.3 dBW = 1.07 watts

PRECEDING PAGE BLANK NOT ATTACHED

APPENDIX E

MECHANICALLY SCANNED ARRAY ANTENNAS

An additional concept that might be considered for this application is a distributed array of low power fixed phase elements that is mechanically rotated by a gimbal system to provide beam pointing. The potential advantages of such a system include:

1. Many low power amplifiers instead of a single high power amplifier will ease thermal dissipation problems and allow for graceful gain degradation as power amplifiers and/or low noise receivers fail.
2. High RF losses in the rotary joints can occur at intermediate frequencies or at low power on transmit, and after the signal to noise level has been established by low noise amplifiers in the receive chain.
3. Each element of the array operates on its boresight. No loss or gain due to scan will occur, and higher gain elements can be used without echelon lobes in the coverage solid angle.

For use on TDAS, element beamwidths of about 15° HPBW, or greater, should be used to prevent high sidelobes in the coverage area. Figure 1 shows the pattern of a square array of dual mode conical horns with a HPBW of 15° . The pattern is plotted out to 26° to show sidelobe levels that would be in the coverage region when the array is mechanically scanned to the edge of coverage. Figure 2 is a pattern of 30° HPBW horns. It can be seen from these two patterns that although echelon lobes can be avoided in the coverage angle by not phase scanning the elements, if high sidelobes are to be avoided as well, the same array constraints will apply as for the phased array design.

The same array configuration described in Appendix A would be a representative approach. Two advantages will result from not scanning electronically.

(4)

First, no phase shifters are required, thus saving approximately 3 dB of insertion loss. Second, operation on the element beam peaks results in an almost 2.4 dB increase in element gain. As a result, the number of elements can be reduced from more than 26,000 to just under 8,000.

This system becomes, in effect, a pallet mounted design including the thermal and weight problems in which the two advantages above must be traded off against a 8,000:1 transmit corporate feed, 8,000 solid state transmitters, 8,000 transmit-receive diplexers, 8,000 circularly polarized horns, 8,000 low noise receive front ends, a 8,000:1 corporate summing network and the fact that the receive summing network must provide for angle tracking as well.

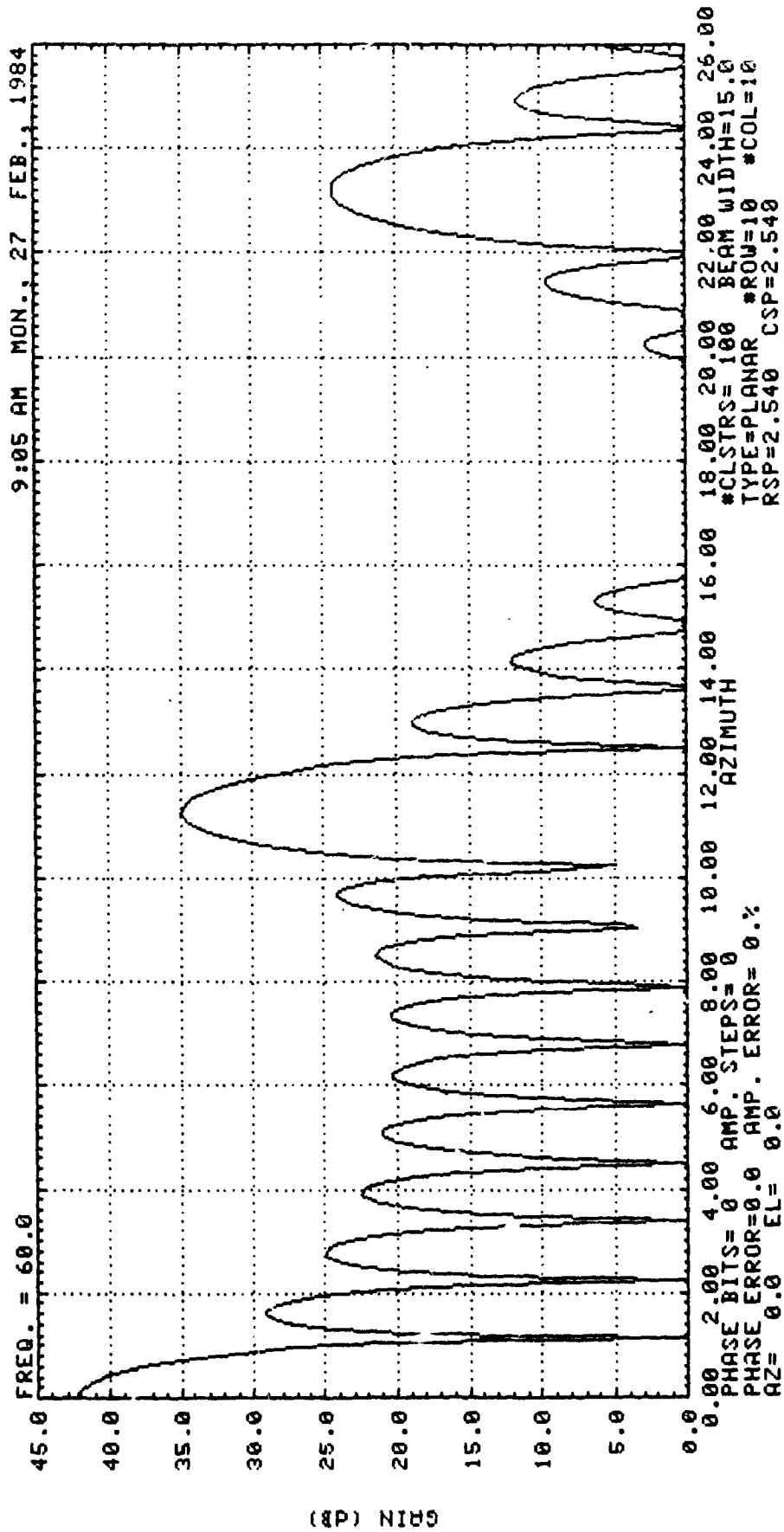


FIGURE 1. - SQUARE ARRAY - 10 x 10 DUAL MODE CONICAL HORNS -
 HPBW = 15° - 1ST ECHELON LOBE AT 11.3°

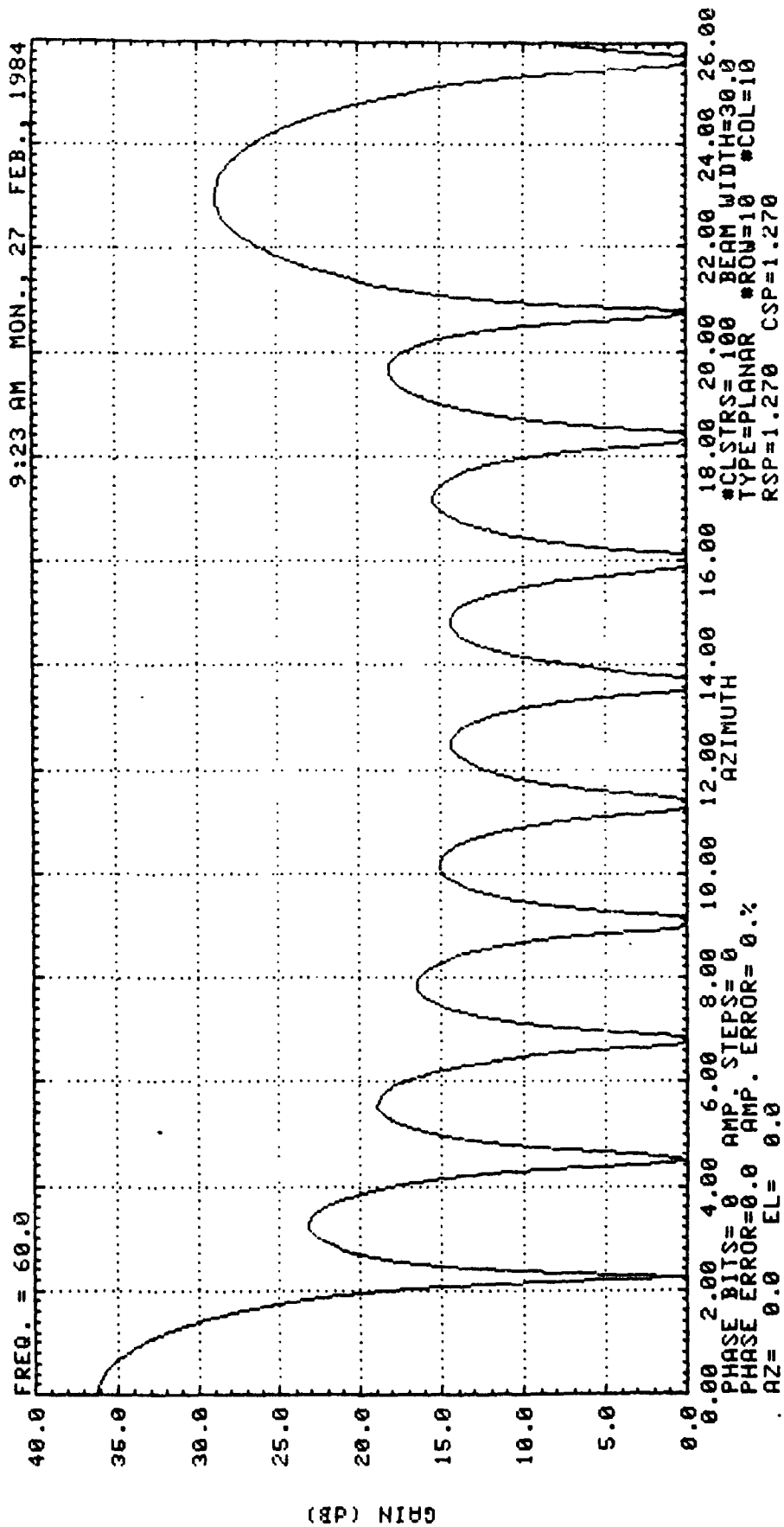


FIGURE 2. - SQUARE ARRAY - 10 x 10 DUAL MODE CONICAL HORNS -
 HPBW = 30° - 1ST ECHELON LOBE AT 23.0°

APPENDIX F

GENERAL ELECTRIC RESPONSE TO NASA GSFC COMMENTS AND QUESTIONS RELATING TO THE PHASE A DRAFT REPORT

On May 14, 1984 NASA-GSFC submitted comments and questions based on their review of the General Electric Phase A Draft Report. This Appendix F contains General Electric's response to these comments and questions in the same format as submitted by NASA-GSFC. Where applicable, the response has been included as a correction in the main part of this report, as noted.

C/Q: Comment or Question by NASA-GSFC

R : Response by General Electric

<u>Report Page No.</u>	<u>General Electric Response to Comments and Questions by NASA-GSFC</u>
1	C: Include page numbers. R: Now included in final Phase A Report.
N/A	Q: Will all backup information for "Preliminary Design and Performance Analysis" be provided? R: The material contained in this report including the appendices represents the preliminary design and performance analysis. The data was developed for this report, deriving from General Electric's experience and prior efforts.
N/A	Q: What is state of the art in low loss rotary joints (using TE ₀₁ mode, for example)? R: The state of the art for low loss rotary joints in the 60GHz band (Ref. R. Sharkey of Alpha Corp.) is found in Alpha Industries TRG Millimeter Wave Products Catalog. A rotary joint consists of two TE ₁₀ mode (rectangular) to TE ₀₁ mode (circular) transitions each with 0.3dB insertion loss. One TE ₀₁ mode filter (0.3dB insertion loss), and one TE ₀₁ mode rotary joint (0.3dB insertion loss).

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General Electric Response to Comments
and Questions by NASA-GSFC

N/A

- C: Show in what way (if any) candidates M, E and H have been optimized before conducting tradeoff study against candidate B, the baseline.
- R: The folded optics design employed in M1, M3, E3 and H1, which allows an effective F/D of 4 and simultaneously corrects for offset feeding effects on the large aperture by a compensating effect on the computer designed subreflector, was developed in a series of trade studies on other programs. The optimized choices on these other programs were scaled in size and frequency to allow for scoring in the tradeoff matrix on the present program. M2 is an estimate of the minimum size configuration to meet the required gain over the coverage angle. M4 is scaled from the LES 8 & 9 designs. E1 and E2 are developed as described in this report to be minimum size, weight, and power designs to meet the gain and coverage requirements.

N/A

- C: Comment - monopulse studies should be part of Phase A.
- R: Monopulse was considered in Phase A to the extent that it constituted a discriminant between candidates. For example, because of monopulse requirements, either stacked rotary joints must be used or forcing the inclusion of a pallet.

12

- C: Performance parameters derived by GE in their proposal (and then later rejected by GE) should be noted as such. These are "Commonality with other Spacecraft", "Communications System Interface", "New Developments", "Quality Assurance/Test Requirements".
- R: The tradeoff matrix was included in the proposal (Table 2.7.7-2) as "typical". During the tradeoff process some of the parameters were eliminated including "Commonality with Other Spacecraft", "Communications Software Interface", "New Developments" and "Quality Assurance/Test Requirements". These four parameters had been introduced by General Electric; i.e., they were not included in the NASA GSFC Statement of Work.

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General Electric Response to Comments
and Questions by NASA-GSFC

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- C: Torque noise is not considered a "minor factor" especially if TDAS carries laser communication systems or if Users carry optical instruments.
- R: "Torque Noise" - i.e., the effect of the acceleration of the moving portion of the antenna on the spacecraft system - has now been added to the tradeoff matrix in response to this comment. See pages 25 & 27 for further data on this subject.

16

- C: "---or a large F/D ratio is used (M2)"
Elaborate on need for large F/D.
- R: Changed (M3) to (M2) on page 16. Dual reflector systems can be shown to have improved scan performance to obtain comparable performance. (number of beamwidths scanned) for a waveguide lens (DSCS III design assumed) a large increase in F/D is required to reduce phase distortion. The need for large F/D ratios to scan apertures by feed displacement is well established in the literature (ref "Scan Limits of Off-Axis Fed Parabolic Reflectors" by A. V. Mrstik, PGAP Vol. AP-27 # 5, Sept 79, p 647-651). Waveguide lens designs with inherently large scan angle have not been considered since the required detailed analysis and design effort exceeds the scope of this study.

17

- Q: Should 6 degrees be shown in figure for M3?
Are there missing angles in figure for M4?
Spell aperture correctly in all figures.
- R: This figure is presented for pictorial comparison only. See later figures for actual scan angles.

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General Electric Response to Comments
and Questions by NASA-GSFC

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- C: Clarify "electronic scanning is limited to the narrow field of view."
- R: Electronic scanning is limited to those solid angles in which a sufficient number of array elements exhibit adequate element gain. For hemispherical coverage, an ideal element cannot achieve more than 3dB of gain (in practice 0dB is a very difficult minimum gain to obtain). Thus, to provide 54dB of gain, 125,892 ideal elements in a lossless, perfectly phased array would be needed for such coverage if mutual coupling problems could be solved. Thus, for any practical antenna of very high gain, electronic scanning is limited to the narrow field-of-view applications, allowing the use of fewer high gain elements.

24

- C: Processor Requirements:
Original specifications called for a dedicated microprocessor for the antenna system - Phase A and B shall reflect this.

Please elaborate on the microprocessor requirements for each candidate.

- R: The original specification requirement for a dedicated processor is now being met. Further evaluation - as part of Phase B - has shown the desirability of dedicated processor. The processor requirements will be evaluated in Phase B for the selected antenna system (B1) only.

24

Q: Loss: What about aperture efficiency?

Since the beam waveguide employs a beam with gaussian field distribution - How is feed horn pattern influenced? - Is special shaping of the subreflector required to increase overall aperture efficiency?

R: How do the gaussian beam modes affect a monopulse feed difference pattern?

- For B1 to B4 the aperture efficiency can be made about equal by proper feed, sub-reflector, and dish design and therefore is not a discriminant, while it is not a well defined parameter for many of the other configurations. In any event, its effect is found in size, weight, power, and complexity impacts.
- The feed horn/beam waveguide combination should be designed together with the sub-reflector and main reflector to optimize the system. If sub-reflector and main reflector shaping is desired to improve aperture efficiency, it can be done just as if the virtual feed were the actual horn. In fact, when optical quality mirrors are used in the beam waveguide an optical illusion can be seen such that the feed appears to be sitting in space at the virtual feed location. The effect of the beam waveguide on the monopulse feed difference pattern is discussed in Appendix B.

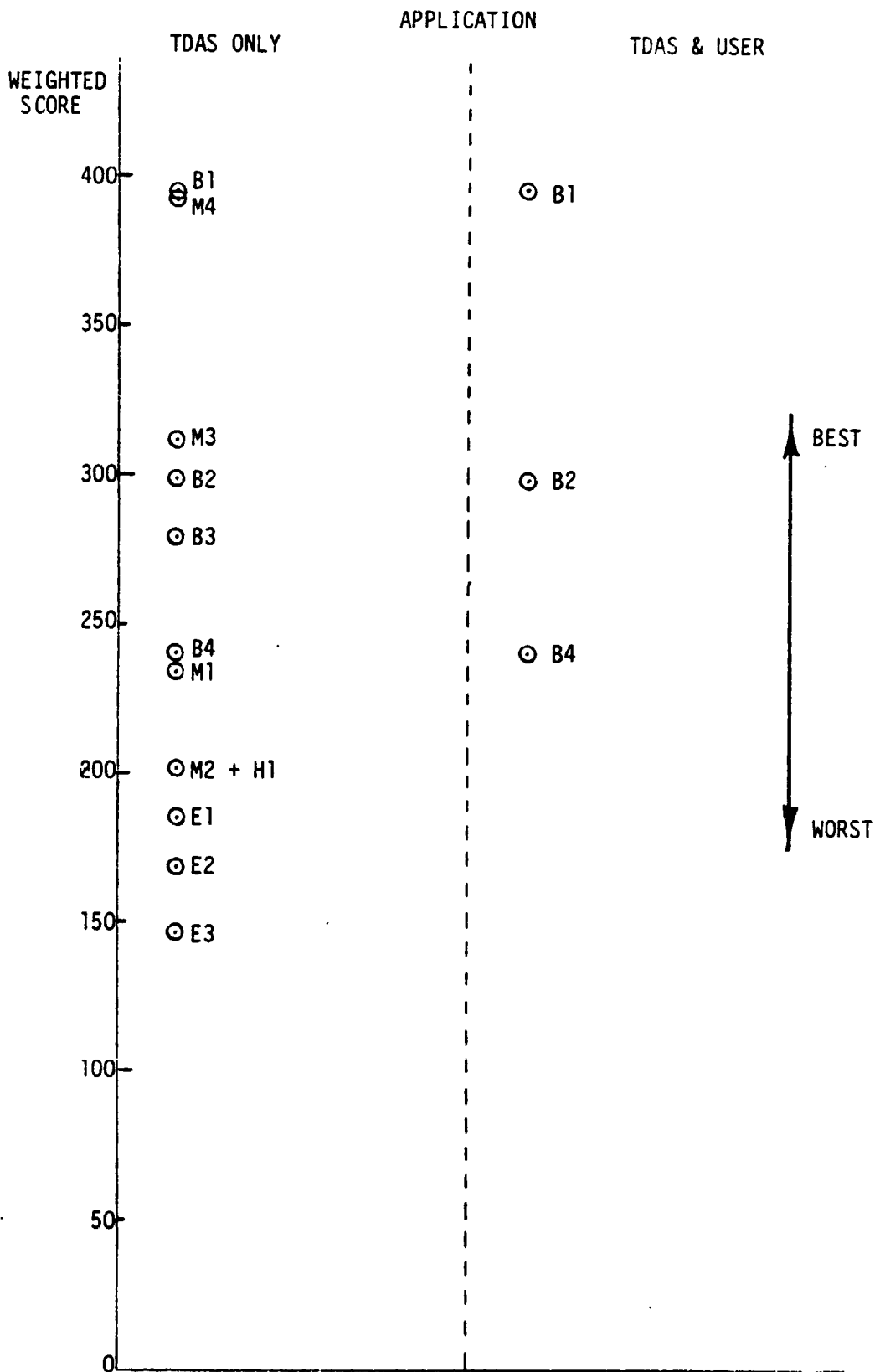
24

C: Environment Protection - Please describe environment extremes and protective measures.

R: A quantitative description of the environment extremes for the various candidates is beyond the scope of this study. With regard to environment protective measures the candidates fall into two basic categories; i.e., whether all the sensitive electronics can be located inside a fixed, readily controllable portion of the antenna system or spacecraft or whether some or all of the electronics is exposed on the moving portion of the antenna, thereby exposing it to varying sun incidence angles. See comments on P. 27 of this appendix for individual scoring.

- 24 Q: Sidelobe Levels - In your statement concerning sidelobes, what is meant by the "temporary" effects and how restrictive are the operational measures?
- R: Temporary implies that a problem might exist during acquisition involving a false lock on a sidelobe. This false lock can be recognized and overridden by operational measures. This can be done through a ground link or autonomously.
- 25 C: If GE chooses not to raise the weight of "cost" and include "tolerances" and "torque noise" as performance parameters - a statement should be made that "the performance parameters and their weights were selected at the technical discretion of General Electric."
- R: "Torque Noise" with a weighting factor of 7 has now been included (see p. 24 and 25). The performance parameters and their weights were selected at the technical discretion of General Electric.
- 26 C: Please emphasize: 5 - major strength
1 - major weakness
- R: Emphasis and scoring example added on p. 26.
- 27 C: Please explain the reasons for relative position of these scores-----
- R: A revised Phase A Tradeoff Matrix has been established including the addition of "Torque Noise" and several numerical corrections - marked by asterisk (*) - have been added. Note that the relative ranking of the candidates was not critically altered by these corrections - see Figure F1.

The individual scores were derived from an analysis of the weight of the moving portion of the antenna. (Using the inertia of each design would have been more accurate, but we lack the detail design data to make such calculations and the relative ranking would not be critically affected).



WEIGHTED SCORES OF CANDIDATES

	B1	B2	B3	B4	M1	M2	M3	M4	E1	E2	E3	H1
Moving Weight (lbs)	37	113	41	62	18	18	28.5	28.5	0	0	0	59
Individual Score	3	1	3	2	4	4	3	3	5	5	5	2
(Weighting Factor = 7)												
Weighted Score	21	7	21	14	28	28	21	21	35	35	35	14

Slew rate determines maximum torque noise; therefore, fine electronic scanning of H1 does not improve its score.

In the following the specific comments/questions relating to p.27 are covered:

<u>Report Page No.</u>		<u>General Electric Response to Comments and Questions by NASA-GSFC</u>
27	Q:	Reliability: M4 > B1 B3 < B4
	R:	<ul style="list-style-type: none">- M4 was rated higher in reliability than B1 because M4 has been flown on the LES 8 & 9 spacecraft, and B1 has not yet flown on a spacecraft.- B4 was rated higher in reliability than B3 because 60GHz rotary joints are catalog items, the flexible waveguide is under development and has not yet demonstrated adequate performance over time.
27	Q:	Development Risk: B1 = B3
	R:	<ul style="list-style-type: none">- Since there are only five levels, equal numbers are approximate. Both B1 and B3 are being developed and are assessed equal risk.
27	Q:	Cost: B4 = B2 < B3
	R:	<p><u>Cost Comparison:</u> The cost of the antenna is a function of the overall complexity and the difficulty of the technology involved. The phased arrays with their high module counts combined with the expense of 60GHz mixers and filters gives these approaches the lowest score.</p> <p>The complexity of the four axis feed motion in M1 and M2 also rates these two a score of 1.</p> <p>The dual rotary joints and the large cassegrain high tolerance reflector give B4 and B2 the next to worst rating.</p> <p>The median score of B1, B3, and M3 are due to their complexity being intermediate among the candidates.</p> <p>Only one candidate has somewhat lower complexity than the overall group and that is M4 where there is only a moving flat plate.</p>

Both B1 and B4, in a practical implementation, will require a thermally insulated pallet while E3, which can only be used for limited scan, can employ three parallel flexible waveguides.

22

Q: Host S/C Impact: B1 > B2 > B3 > B4
R: The relative impact on the host S/C was assessed as follows: B1 sweeps out the minimum volume and requires the minimum weight to be scanned. B2, B3 and B4 are rated relatively by the size of their physical apertures, as vehicle surface area and stowage space available to antennas is usually in short supply.

27

Q: Integration and System Test: B1 >> B2
R: The pallet mounted electronics on B2 must take on differing orientations with respect to the sun and thus must have heat pipes in two dimensions. Therefore, there is only one possible orientation of this antenna in which thermal/vacuum testing can be done. It thus becomes very difficult to simulate different sun angles in test, as the solar simulator does not move around the thermal/vacuum chamber, but the spacecraft must be rotated. The B1 configuration has the electronics mounted to North and/or South oriented panels of the spacecraft and no heat pipes are required. The same is true for M3, M4, and H1.

27

Q: Beamwidth: B1 = B2 = B3 = B4 = 5
R: The wider the beam the higher is the score. The beamwidths of B1 and B2 are the same (same aperture and distribution). B3 has a beamwidth only 10% smaller and cannot be separated from B1 and B2 on a scale of 1-5. B4, however, should be rated 3 as its beamwidth is 30% smaller than B1 (see Matrix, P. 27). The low scores go to E-Configurations with large apertures and small beamwidths.

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General Electric Responses to Comments
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- 27 Q: Loss: $B1 = B2 = 5$; $B3 = 2$, $B4 = 1$.
Please relate to beamwidth score.
R: B2 has its electronics directly behind its feed and the beam waveguide between the virtual feed and the horn on B1 has exhibited a measured loss of less than 0.2dB in breadboard tests. B3 will have about 1dB of additional loss in the flexible waveguide if the design goals for the dielectric flex guide are met. To make up this loss, the aperture must be increased by about 10% in diameter and the beamwidth is reduced by 10% as a consequence. The two rotary joints for B4 with their interconnections will result in a loss of about 3.1dB which requires an increase of more than 30% in aperture diameter.
- 27 Q: Polarization Purity = $E1 = E2 = E3 = 1$
R: The electronic scanning configurations require that element patterns be summed well off their peaks (i.e., at the -3 to -5dB level); in addition, mutual coupling between horns degrades circularity as a function of scan angle.
- 27 Q: Processor Requirements = $B1 = 4$ not 5
R: There is a slight penalty in processor requirements for B1 because of the coordinate transformation required by having the monopulse horn fixed to the spacecraft rather than with respect to the antenna as is the case for B2-B4.
- 27 Q: Weight and Power
R: Additional data has been included below in support of the relative scoring position. See Table F1 for a detailed weight budget for configuration B1 and weight and power scores of all candidates.

Additional information was requested on the relative weight differences of some of the candidates. These are supplied below all compared to the baseline configuration B1.

TABLE F1

CONFIGURATION B1 (BEAMWAVEGUIDE) - WEIGHT BUDGET

<u>Aperture</u>	<u>Weight (lbs)</u>	<u>Power (Watts)</u>
Reflector	10.5	-
Insulation	<u>5.9</u>	-
	16.5	

MM Wave Electronics

Feed	.1	-
Monopulse Modulator	.8	1.4
Transponder	12.8	27.9
Local Oscillator	8.8	9.4
Power Conditioner	6.1	7.7
Thermal Control	<u>1.0</u>	-
	29.6	46.4

Gimbal

Mechanism	20.2	1.4
Thermal Control	<u>.6</u>	<u>4.0</u>
	20.8	5.4
Pedestal	12.5	-
Position Controller	<u>17.9</u>	<u>7.5</u>
	97.3	59.3

WEIGHT SCORES

	<u>B1</u>	<u>B2</u>	<u>R3</u>	<u>R4</u>	<u>M1</u>	<u>M2</u>	<u>M3</u>	<u>M4</u>	<u>E1</u>	<u>E2</u>	<u>E3</u>	<u>H1</u>
Actual Weight (lbs)	97	133	101	122	138	250	115	125	3660	3639	325	167
New Individual Scores	5	4	5	5	4	2	5	4	1	1	1	4
New Weighted Scores	40	32	40	40	32	16	40	32	8	3	8	32

POWER SCORES

Actual Power (Watts)	59	83	64	64	64	64	59	59	10 117	10 117	59+	64
New Individual Scores	5	2	4	4	4	4	5	5	1	1	1	4
Weighted Scores (X7)	35	14	28	28	28	28	35	35	7	7	7	28

+Power for Phase Shifters not included

R2

B1 weight 97.3 lbs.

+	21.1	electronics enclosure
-	8.5	pedestal (support only)
+	4.8	mechanism (more moving mass)
+	1.7	position controller (more moving mass)
+	<u>17.3</u>	electronics thermal control

36.4

TOTAL 132.7 lbs.

B1 weight 97.3

+	17.5	dish dia. 69" vs 48" Δ weight
+	7.5	rotary joints, connecting waveguide, support and thermal control for monopulse.

25.0

TOTAL 122.3 lbs.

M4

B1 weight 97.3

+	6.0	flat plate (67") Δ over 48" parabolic
+	16.5	parabolic ref (48")
+	<u>5.2</u>	support structure

21.7

TOTAL 125.0 lbs.

B3

B1 weight 97.3

+	3.6	aperture Δ over 48" aperture
+	<u>0.1</u>	flex waveguide

3.7

TOTAL 101 lbs.

R1

Assumption

Graphite Epoxy Structure
MIC Electronics
Electro formed thinwall waveguide components

Electronics Housing

84 lbs.

Power Differences (B3, B4, H1)

B1 = 59.3 watts

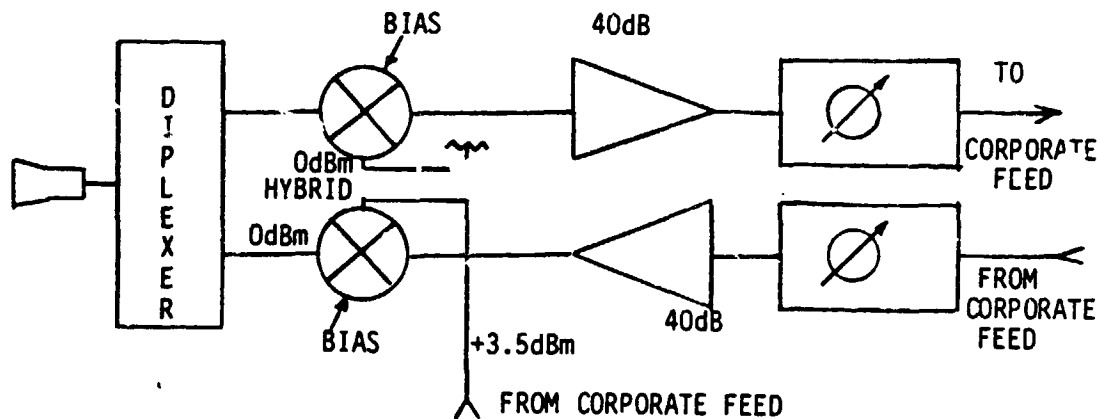
B3 and B4 use an additional 4.7 watts to temperature control monopulse assembly as moving antenna.

H1 uses 4.7 watts for electrical control of variable power divider network.

M1 and M2 uses an additional 4.7 watts for thermal control of feed assembly.

R1

For the purpose of DC power assessment each element consists of the following:



Assumptions:

Power output per module is insignificant because of large number of elements, therefore design is driven by S/N considerations.

Insulation

30 lbs.

Power Conditioning

10,117 watts at 0.1 lb/watt = 1012 lbs. (very optimistic)

Electronics - (Phased Array Elements & Processor)

.02 lbs/in³ x 99981 in³ = 1999.6 lbs.

Thermal Control

28w/ft² radiation area

1.5 lbs/ft² (1.5" heat pipe augmented panel)

$\frac{10,117}{29} = 348.9 \text{ ft.}^2$

348.9 x 1.5 = 523 lbs.

MM Wave Electronics

Transponder	12.8
Local DSC	8.8
Power Cond	6.1
Thermal Cont	1.0
Enclosure	<u>12.5</u>

41.2 lbs.

Total Weight E1 - 3660 lbs.

E2

Same as E1 except

Electronics Housing	-64 lbs.
Small Parabolic Reflector	+ 3 lbs.
69" Parabolic Reflector	+34 lbs.
Reflector Support Struc.	<u>+6.3 lbs.</u>

-20.7 lbs.

Total Weight E2 - 3639 lbs.

Lo Corporate Feed

Four layers 0.6dB loss per layer = 2.4dB

$$4^4 = 256$$

$$10 \times \text{LOG}(256) = 24.1\text{dB} \quad \underline{24.1\text{dB}}$$

Power Division & Loss 26.5dB

$$3.5\text{dBm} + 26.5 =$$

=30dBm (1W) at 10% eff. or =10 watt DC/256 elements for Lo power

Need 104 sub-lo's to feed 26,569 elements. . 1040 watts DC

Control Logic and Processor

2 x 64K Redundant Memory	25W
Processor	15W
Buffer Memo	10W
Buss Drivers	10W
- 53,138 Decoder & Latches	
50u watts ea.	<u>3W</u>
	63W

Preamplifiers

$$26,569 \times 2 = 53,138$$

129.8mw DC per amplifier

$$= 6,898 \text{ watts}$$

Phase Shifter

$$26,569 \times 2 = 53,138$$

30mw DC per phase shifter

$$= 797.0 \text{ watts}$$

Total

Local Oscillator	1040	
Preamplifiers	6898	
Phase Shifters	797	
Control Logic & Processor	<u>63</u>	
	8798	
DC to DC Converter	<u>1320</u>	85% Eff.
	10,118	watts

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General Electric Responses to Comments
and Questions by NASA-GSFC

Q:

Environment Protection:

B3 = B4 = 4 then B1 = 5

All M's = 5

All E's = 1

R:

- The ratings for environmental protection are based upon where the sensitive electronics are located (i.e., hard mounted to the spacecraft in a protected area = 5, while mounted behind the phased array feed horns = 1.
- B1 houses all electronics inside a fixed pedestal; therefore the rating of 5. B3 and B4 have the monopulse modulator exposed on the moving antenna portion; thus the rating of 4.
- All the M's confine the electronics on the fixed enclosure; therefore the rating of 5.
- The E's have the electronics enclosed; however, the total volume is large and dissipates a very large amount of heat, therefore exposing it to the thermal effect of varying sun angles; thus a rating of 1.

33

Q:

Include cost estimates used to derive scores. Cost factors relative to the baseline are acceptable.

R:

The relative cost factors are given above in the comments for p. 27 "Cost Comparison".

- 33 Q: Why is power the same for B3, B4, M1, M2, H1?
- What constitutes weight difference between B3 and B4 (yet power is the same).
- In B3 is doubling in volume due solely to aperture diameter change?
- Explain derivation thoroughly: weight and power for E1 and E2.
- R: Volume Assumptions
B3 is not double the volume of B1 only
 $21 = 1.312$
16
1.3 increase is due to 53" vs. 48" aperture. The other items have been covered under weight and power (p. 27) above.
- 34 C: Show diagrams depicting location of interference regions.
- R: An interference study will be conducted during Phase B.
- 41 Q: What lengths of waveguide runs were assumed for B1, B2, B3?
- What were the losses?
- R: For B1 and B2 only a few inches of waveguide are needed in the sum channel RF path. For B3 three parallel waveguide runs of about 15" are required, including about 8" of elliptical flexible dielectric guide, as well as flex to rigid adapters. The losses for B1 and B2 are less than 0.1dB. For B3 the loss is estimated at just under 1.0dB.
- 42 C: Give more details of the flexible waveguide used in establishing the scoring for this candidate (B3) stating characteristics at 60GHz.
- R: Flexible waveguides (and rotary joints) for 60GHz have been identified as specific study topics for Phase B. The preliminary evaluation was done on the basis of vendor information (W. L. Gore & Associates, Inc) on dielectric waveguide. The waveguide is fabricated from expanded PTFE (Polytetrafluorethylene). The dielectric constant is controlled by the void content in PTFE. This type waveguide has been developed to provide an insertion loss of 2dB/meter including the loss in input and output launcher (at 50GHz).

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- 44 C: Give more details of the design of the rotary joints assumed in scoring this candidate (B4) stating characteristics at 60GHz.
R: See description at beginning of Appendix F.
- 52 C: Describe lens used to assess capability of candidate "M2".
R: The lens used to assess M2 is a square waveguide design similar in concept to that employed on DSCS III. It is zoned to minimize its weight. No sophisticated phase shifting techniques were assumed because of the 60GHz frequency.
- 55 C: Give number and type of rotary joints used.
R: 3 rotary joints are required for the pantograph and 1 two-axis rotary joint for feed tilt in 2 planes.
- 62 Q: How large is "large enough"?

Give plate stability requirements for candidate M4.

R: - As in the case of the beam waveguide, the flat plate is in the near field of the paraboloid aperture where the beam can be shown to be tightly confined. Thus, it is only necessary to insure that for all plate tilt angles that a cylinder projected parallel to the dish axis from the dish rim intersects the flat plate with about one wavelength (0.2") extra plate area outside the intersection.
- The plate stability requirement for the M4 configuration is twice that for the baseline movable paraboloid since the beam will move two degrees for every degree of relative motion of the flat plate.
- 70 C: Please give contract and report number for reference 2.
R: Added on p. 70 of main report.

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General Electric Responses to Comments
and Questions by NASA-GSFC

- 75 C: Please give feed horn dimensions for E3.
R: The feed horns employed in the design of E3 are simple conical feeds radiating the TE₁₁ mode. They are approximately 0.6" in diameter and 1.5" long.
- 84 C: "-----were presented to NASA/GSFC on 23 February 1984. A written draft of the Phase A report was released March 16, 1984, and this Phase A final report contains additional information in response to NASA/GSFC questions."
R: Included on p. 84 of main report. Also see p.4 of main report.
- 90 Q: "Two levels of variable power dividers (VPDS) are required with an insertion loss of 1dB per level and 12 levels . . . with insertion loss of .2dB per level." Therefore, does loss equal (2 x 1) + (12 x .2) or 4.4dB?
R: Correct - Values have been corrected on p. 90 (Appendix A).
- 99 C: Beam waveguide antenna feed would be more appropriate.
R: Corrected on p. 99 of main report.
- 113 Q: If R = 6371 Km, then are Users looking through attenuating atmosphere at 125.96° and 104.17°?
R: Yes - these angles represent the extreme angles of tangents to the earth's surface.

Additional Questions

- A) What is RMS surface tolerance of reflector (using beam waveguide)?
- B) What is aperture efficiency fo proposed 48" diameter parabola? What is aperture efficiency of 72" parabola of Figure 8, page 110?
- C) What is 3dB beamwidth?
- D) Can you point the system within 1/10 of the 3dB beamwidth?
- R: These four additional questions imply that the optics for the beam waveguide 60GHz crosslink antenna already exists. As pointed out in the proposal, a well designed 1M (or 40") aperture would probably be adequate to meet the 54dB gain requirement. A 48" baseline was chosen as a conservative approach to allow some margin for error, so that an overall antenna efficiency of 45% could meet the requirements. If a shaped subreflector and main dish are used, and $\pm .005$ " tolerances are

held, and if optimum solar protection is employed, a peak gain of 56dB is possible, including losses due to the beam waveguide, monopulse, polarizer and mode adapter (70% overall antenna efficiency). Dish shaping and holding such tight tolerances might not turn out to be cost effective for any given application, however.

The half power beamwidth for the 48" baseline antenna is about 0.3° . Pointing to $\pm .03^\circ$ can be done, but it might not be cost effective for a given use. The NASA specified requirement in the SOW is $\pm .05^\circ$.

The following pages of the main report have been updated as a result of the addition of "Torque Noise" and corrections in weight and power: 25, 27, 29, 31, 33, 67, 71 and 75.